Multiband Agile Neo-Sensor (MANS)

(a novel warfighter concept based on emerging DE technology)

Air Force Research Laboratory

Directed Energy Directorate

Sponsored in part by:

AFOSR

Beam Projection & Compensation Group

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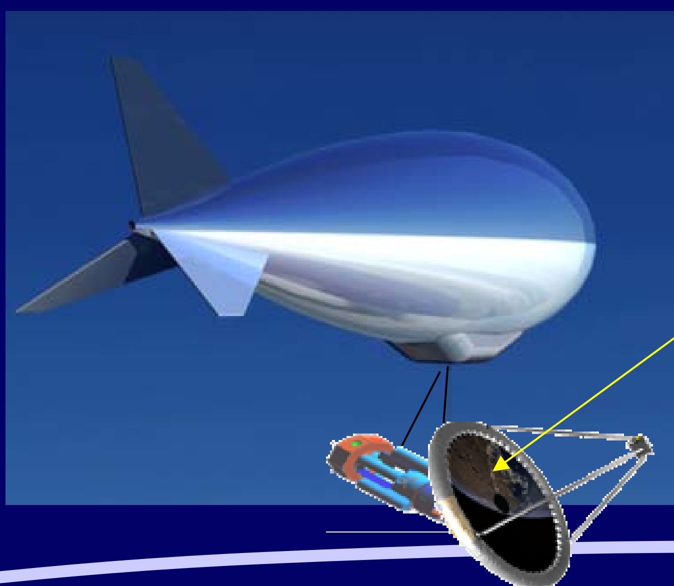
+ others (see individual briefing)

MANS Concept

3-meter aperture multi-band passive or active imaging system utilizing ultra-lightweight optics, advanced wavefront control,

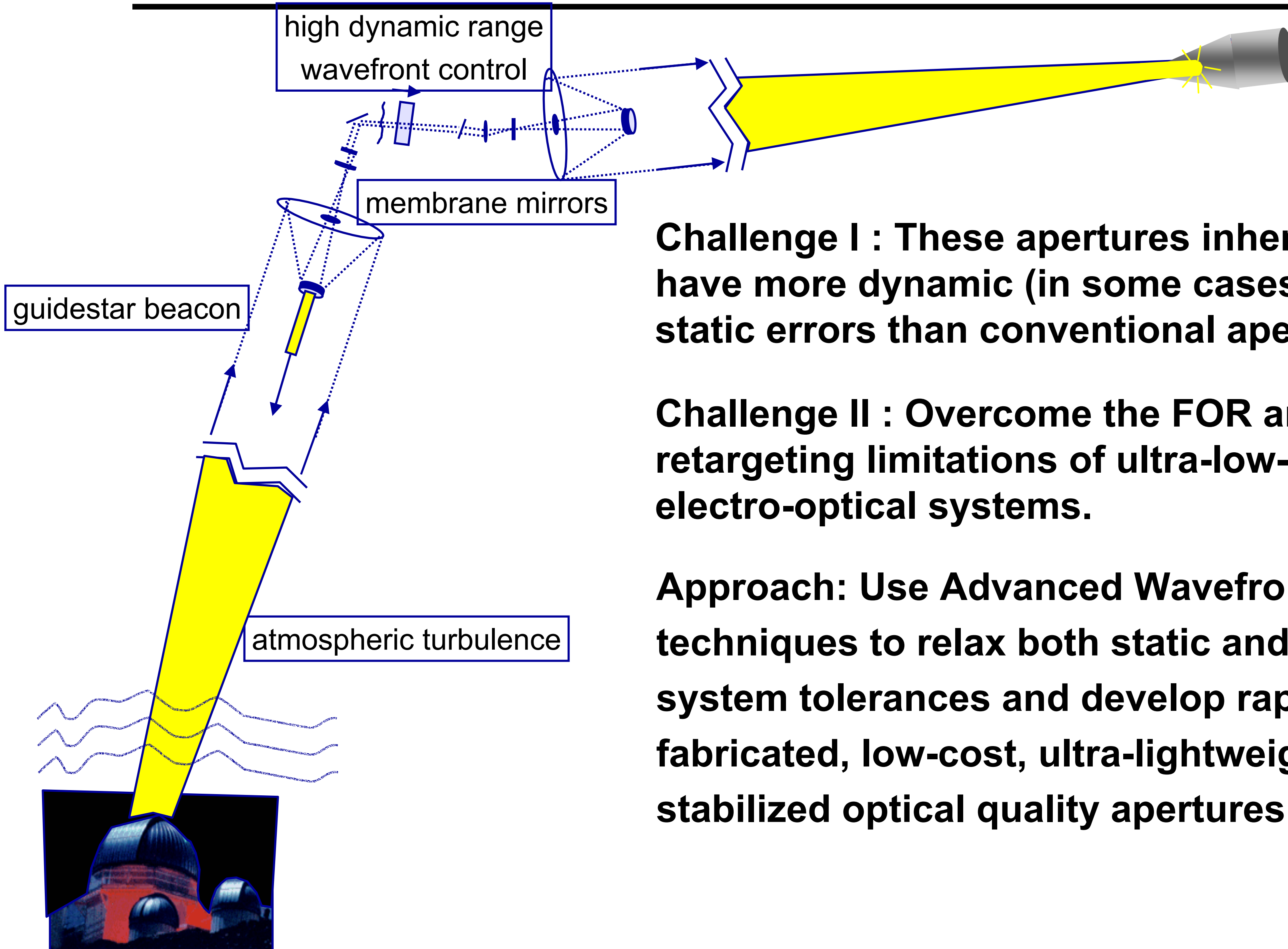


And one of the following:

- high altitude airship
- balloon
- space platform
- mobile ground based

Strategic Vision

Enable rapid-fab, low-cost, ultra-low-mass optical elements for agile imaging and (later) HEL beam projection systems



Challenge I : These apertures inherently have more dynamic (in some cases) and static errors than conventional apertures

Challenge II : Overcome the FOR and rapid retargeting limitations of ultra-low-mass electro-optical systems.

Approach: Use Advanced Wavefront Control techniques to relax both static and dynamic system tolerances and develop rapidly fabricated, low-cost, ultra-lightweight, stress stabilized optical quality apertures

MANS Mission

– Space Situational Awareness (SSA)
– Boost phase tracking
– Missile launch detection
– Space shuttle inspection
– Intelligence, Surveillance, Reconnaissance (ISR)
– Border Patrol
– Forest Fire Detection and Management
– Traffic Management
– Pollution Detection
– Law Enforcement

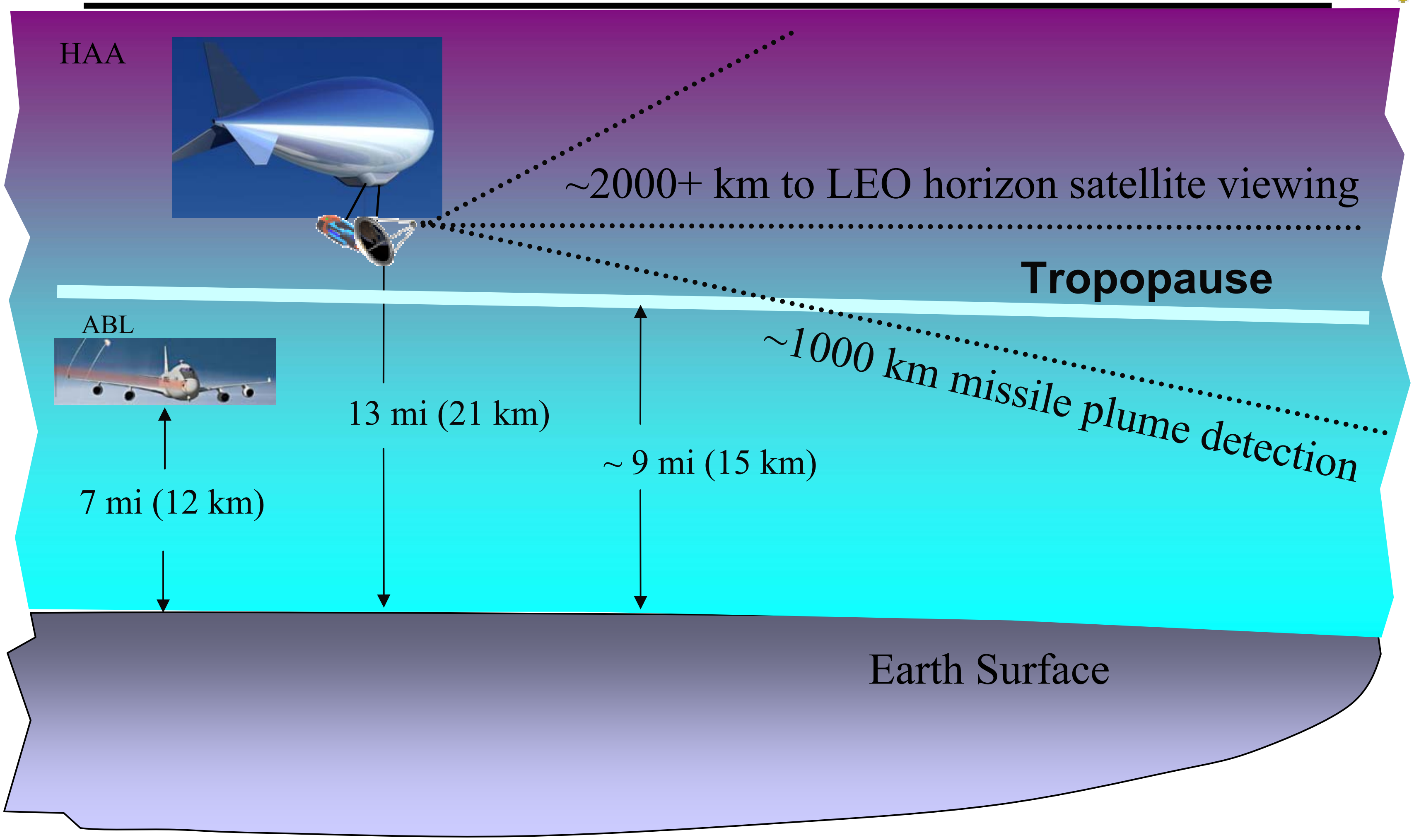
Main Point

If you try to put a conventional lightweight 3-meter diameter agile optic on a High Altitude Airship, it will no longer be at a high altitude.

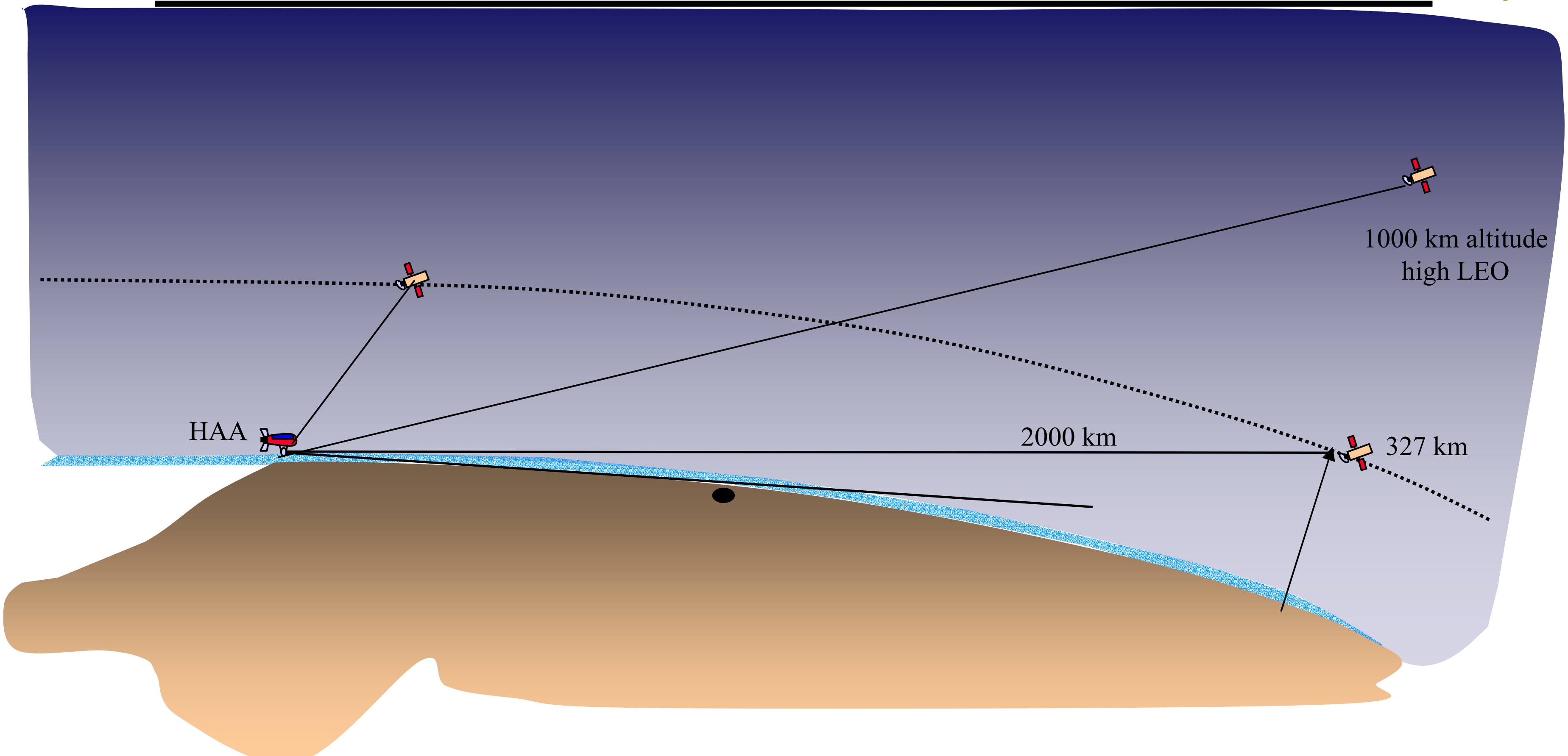
Advantages of <u>any</u> optical system mounted to the High Altitude Airship

Tangential tropopause imaging at 70kft
A powerful tool for viewing missiles & satellites

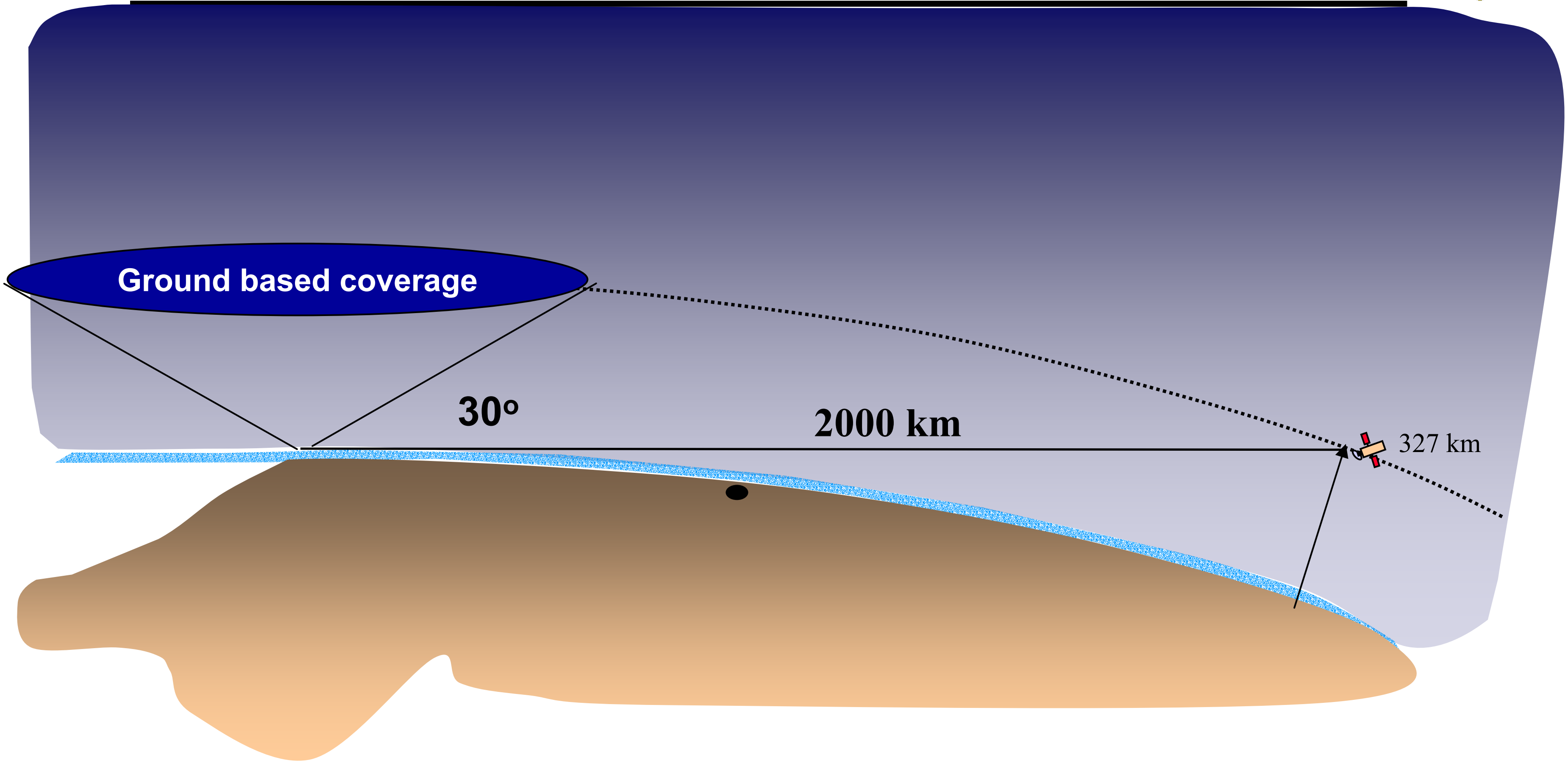
(*Minimal atmospheric aberrations… $r_0 \geq 50$ cm*)



Missiles, space objects , and SSA



HAA vs ground based coverage



What could AFRL's 3-meter diameter MANS do on the HAA?

- Significant light gathering capability
- High resolution
- Minimal atmospheric aberrations
- Relaxed structural tolerances
- System capabilities: agile λ, bandwidth, and novel opto-mechanics

Passive imaging capabilities

Range-to-target	Res (cm)	S/N
Space shuttle (200km)	4	~60*
Vertical (500km)	11	
Tangential tropo (2000km)	44	


What makes us think we can do this?

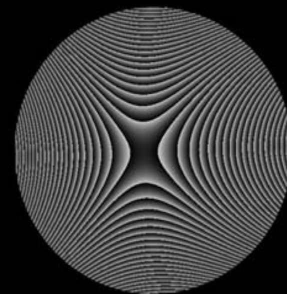
The five enabling Technologies

- Advanced WFC*
- Agile narrowband filters (NMSU)
- Wide Dynamic range WFS* (UAH?)
- Ultra-lightweight optics (including optical windows)*
- High Altitude Airship HAA (MDA) or others

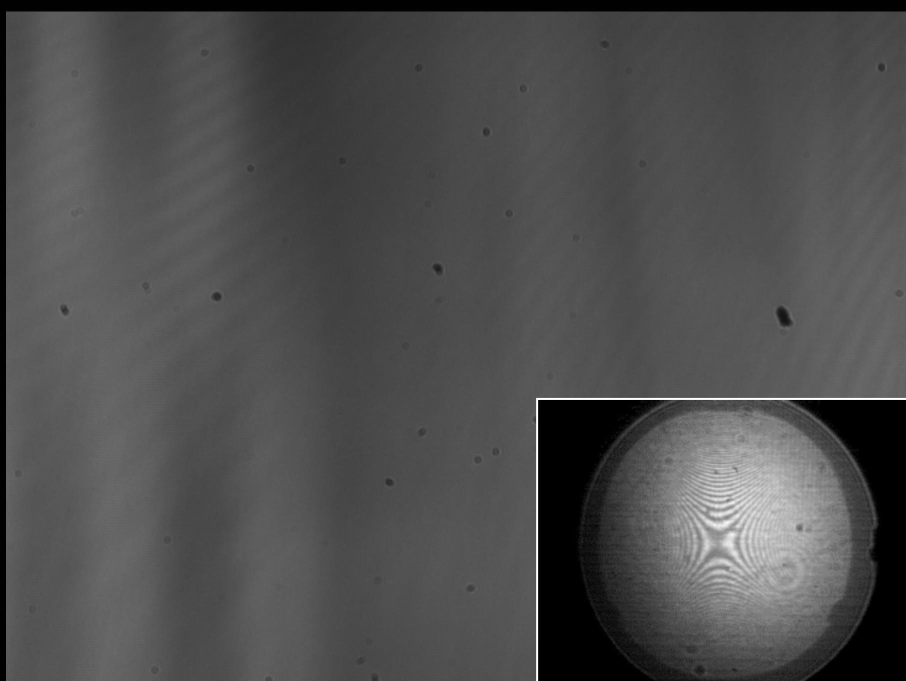
* DE developed technologies

Compensated Telescope: 10-Degree Off-Axis Aberration Compensation

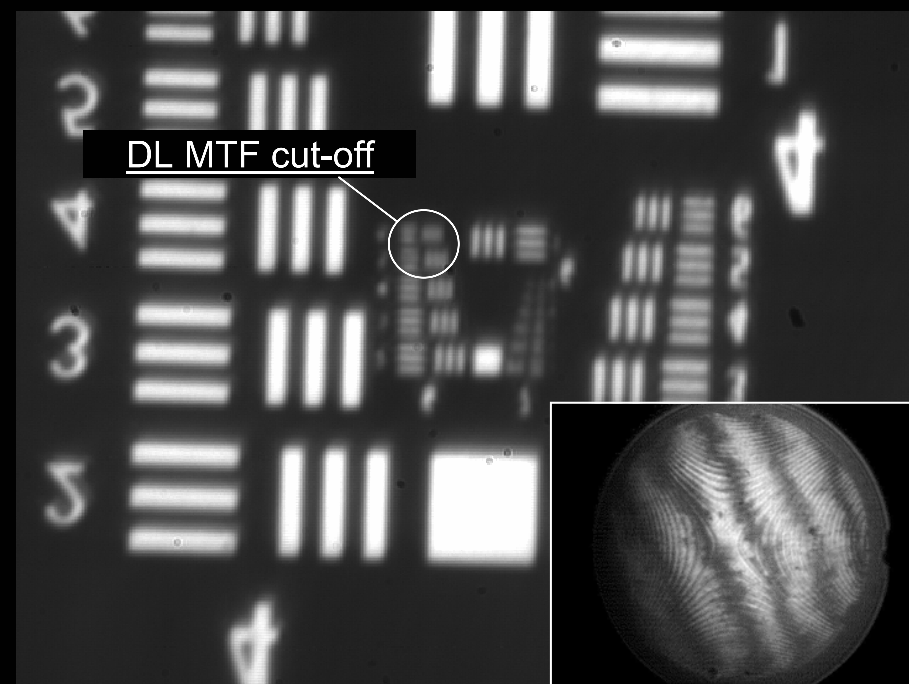
factor-of-70 increase in FOR



programmable diffractive optic phase profile

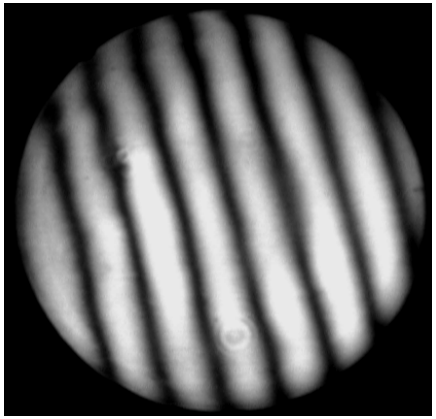


without compensation
~ 40λ p-p aberration



with compensation
diffraction-limited performance

Pressure Augmented Membrane (PAM)

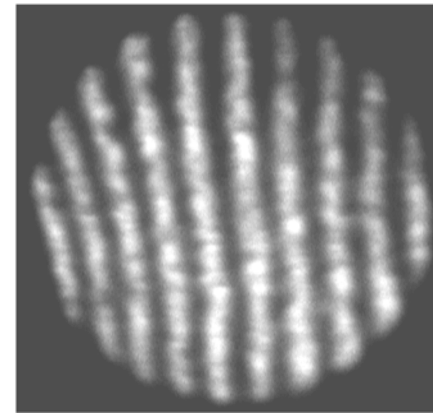


Thickness variation (rms) @ 633 nm

λ/20 @ 10 cm dia

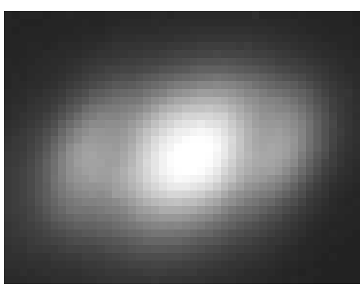
λ/8 @ 28 cm dia

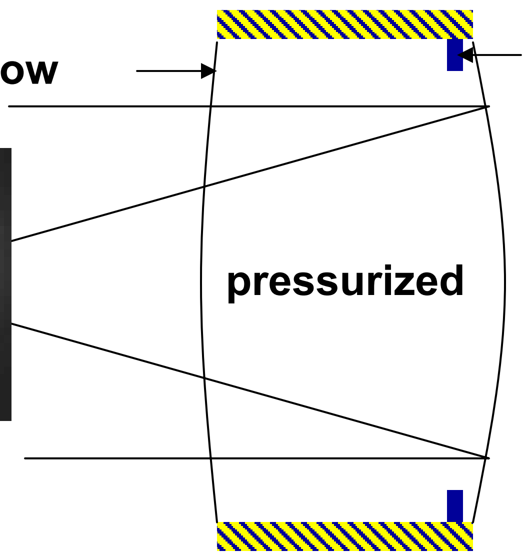
λ/20 @ 90+ cm dia



Composite ring

Membrane window

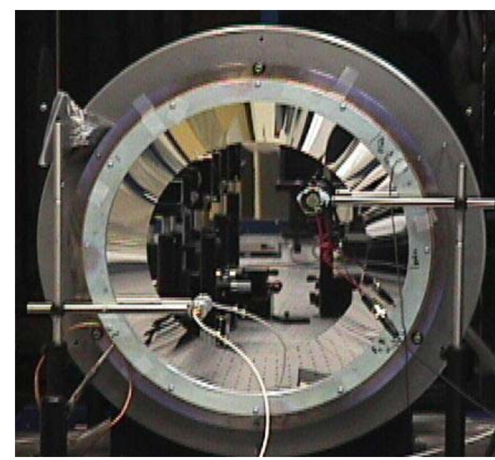




Boundary control

Membrane mirror

λ/5 at 15 cm dia



Surface roughness < 1 nm rms

Comment

- All involved technology is a reasonably new development
- The Technology Readiness Level is quite varied
  - e.g.
    - Large planar polyimide film are well developed
    - Doubly curved films less developed
    - High energy laser film structures even less
- Expect technology to become largely available by 2009
- W/O a short explanation of AWC technology the believability of an optical quality membrane telescope is difficult to accept

The five enabling Technologies

- Advanced WFC*
- Agile narrowband filters (NMSU)
- Wide Dynamic range WFS* (UAH?)
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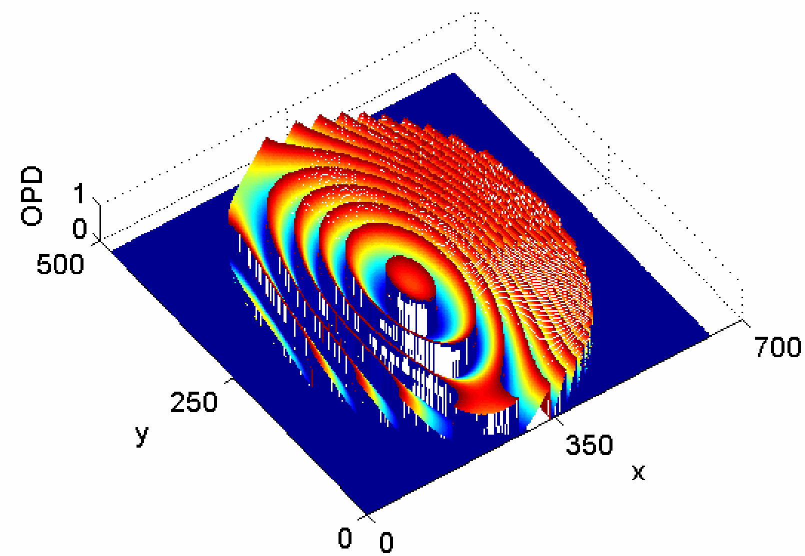
- High Altitude Airship HAA (MDA) or others

* DE developed technologies

Diffractive Wavefront Control for Multi-Wavelength Applications

Jim Rotge, Ray Dymale, and Donald Lubin
Boeing North America Inc. PO Box 5670
Albuquerque NM 87185

Mark Gruneisen and Lewis DeSandre
Air Force Research Laboratory
Directed Energy Directorate
Kirtland AFB, New Mexico 87117

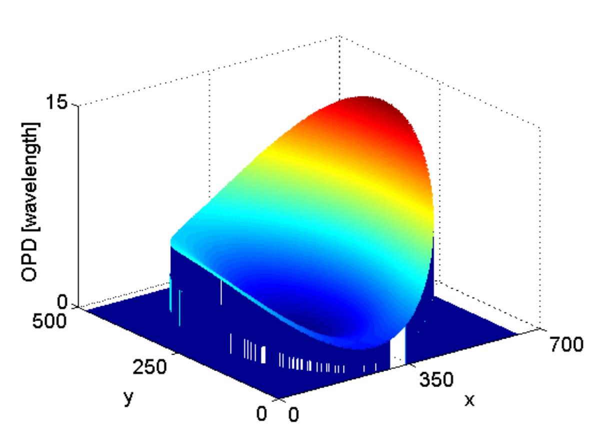


This work is supported by
AFOSR - Dr. Kent Miller
EOARD - Dr. Alex Glass

Diffractive vs. Conventional WFC

2-dimensional dynamic operation

Conventional WFC



large-range OPD

Aberration Compensation Mechanism:

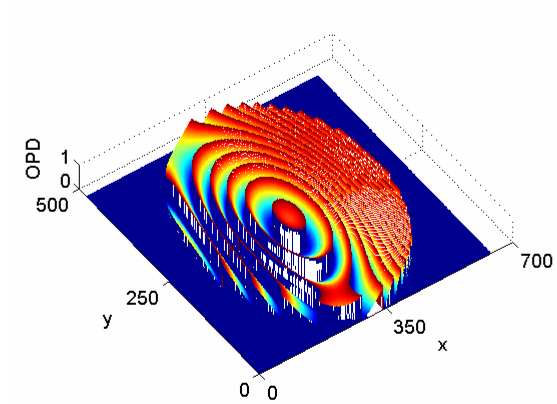
Optical Path Subtraction

$OPD_{ab}(x,y) - OPD_{deformable\ mirror}(x,y) = 0$

Advantage

Wavelength insensitive!!!!

Diffractive WFC



low-range mod_{λ}(OPD)

Methods

- reconfigurable modulo-λ phase gratings
- real-time holography

Aberration Compensation Mechanism

Diffractive Phase Subtraction

$\Phi_{ab}(x,y) - \Phi_{modulator}(x,y) = (2\pi\, \Delta\lambda / \lambda_{ab}\, \lambda_{modulator})\, OPD_{ab}(x,y)$

Advantages

Potentially faster with low-throw requirement

More mature technology for large aberration compensation

Issues

Diffraction Efficiency

Wavelength Dependence

Hardware Approaches to High-Resolution Diffractive Phase Modulators with 100,000s of elements

1. Liquid-Crystal-on-Silicon Phase Modulators {~512x512 array}
   - Boulder Nonlinear Systems
   - Kent State Liquid Crystal Institute

2. Optically Addressable Liquid-Crystal Spatial Light Modulators
   - Institute for Laser Physics
   - Hamamatsu Photonics K.K.
   - Quinetiq

2. Cascaded EASLM/OASLM {~640x480 array}
   - Hamamatsu Photonics K. K.
   - Quinetiq

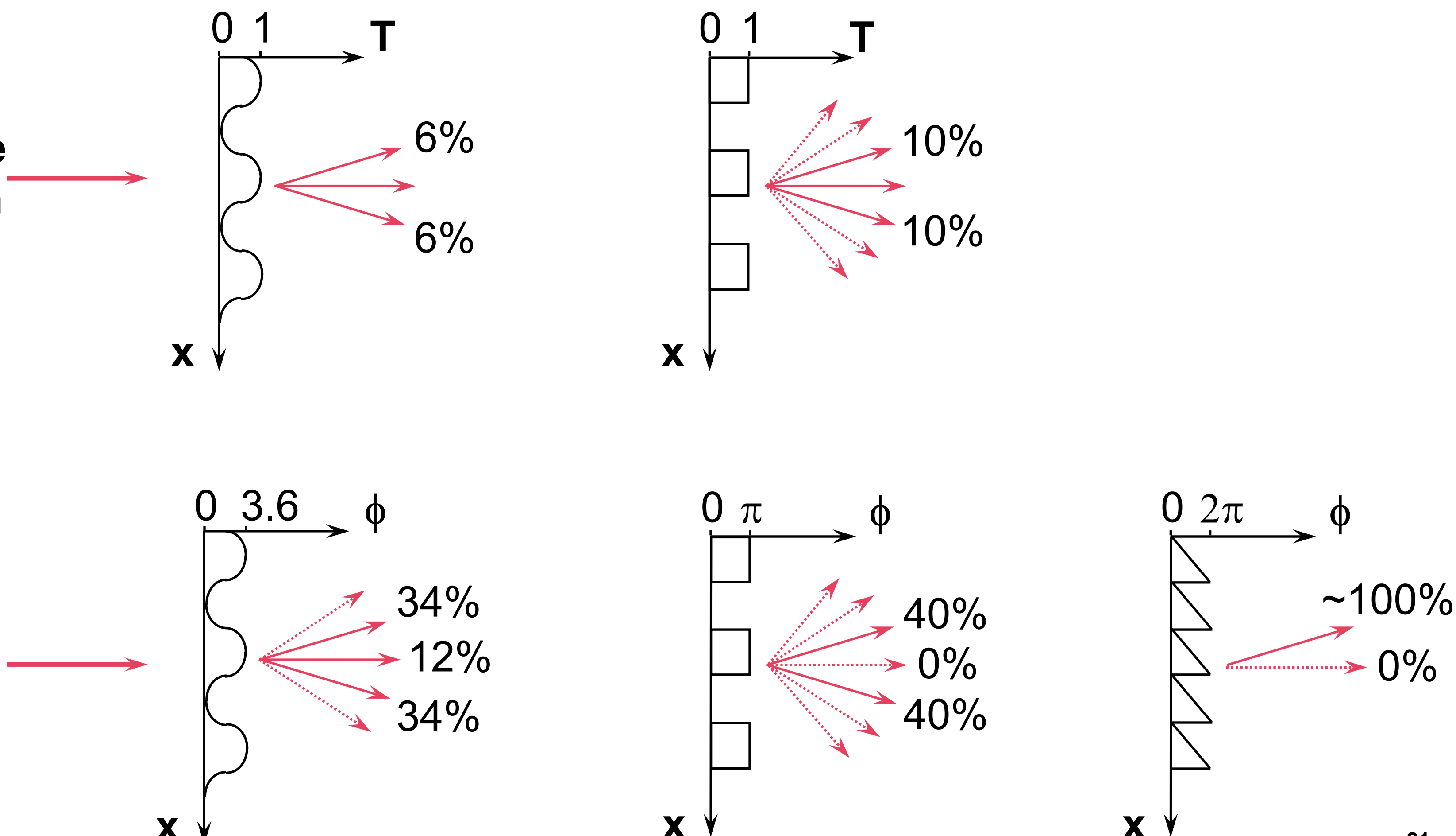
3. High-Resolution MEMS Mirrors {array sizes tbd}
   - Boston Micromachines
   - Optron Systems
   - Intellite, Inc.

1. Diffraction Efficiency

Maximum Diffraction Efficiencies for Thin Diffraction Media

{Scalar Theory of Diffraction}

	analog modulation	**binary modulation**	**mod-λ (blazed) modulation**
amplitude hologram			
phase hologram			



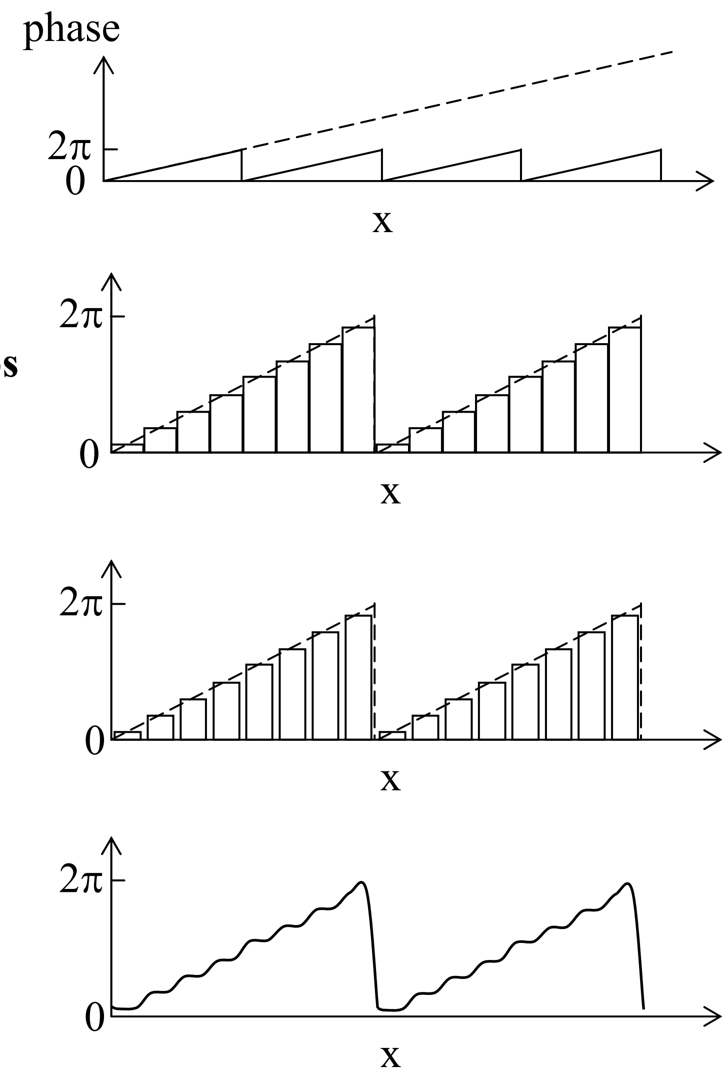
Important Practical Issues to Achieving High Optical Efficiency

a) Theoretical ideal

b) Discrete phase steps

c) Limited fill factor

d) Influence function

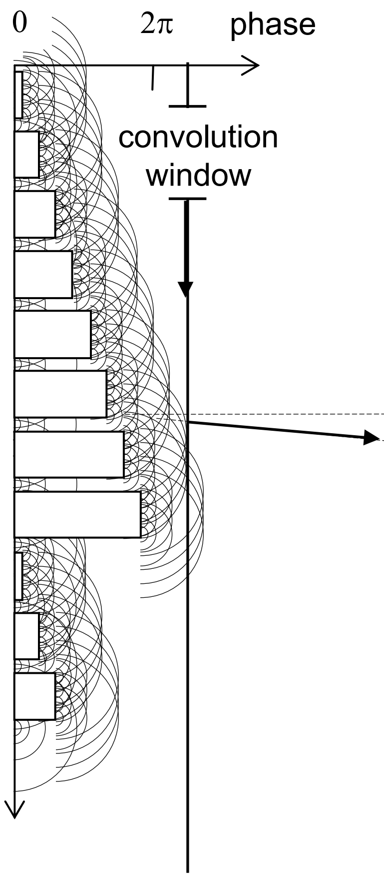


<u>Important Issues</u>

1. Accuracy of phase resets
2. Discrete phase steps
3. Fill factor
4. Localization of resets
5. Linearity of phase response

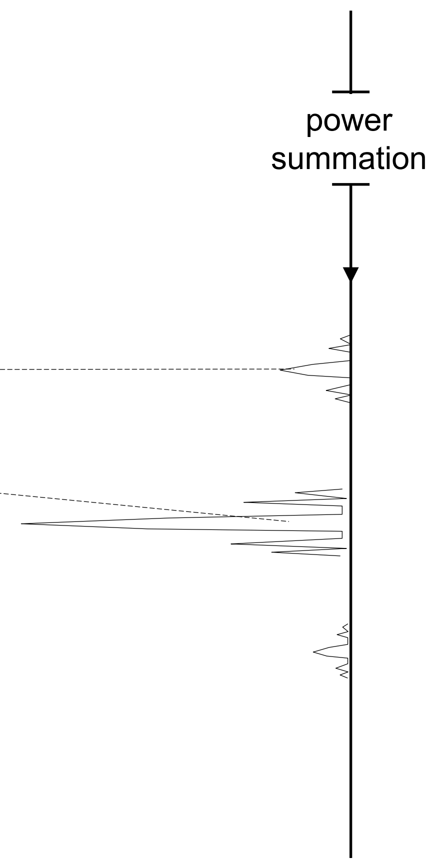
Optimization of Diffraction Efficiency

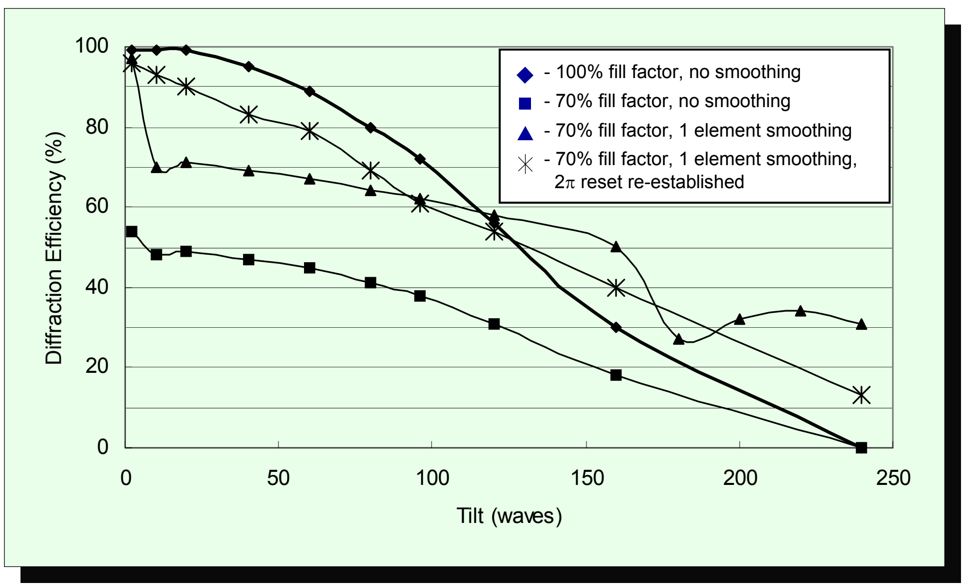
Physical Optics Model for Numerical Computation of Diffraction Efficiency



<u>Features of Model</u>

1. 480 pixels in a linear array
2. 10 Huygen's sources per element
3. Discrete phase modulation
4. Variable fill factor
5. Variable influence function



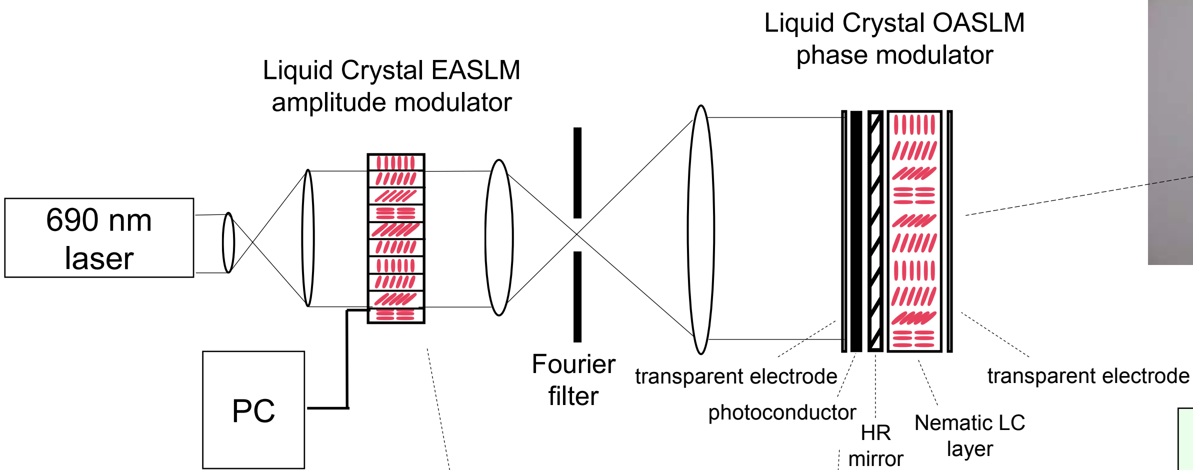


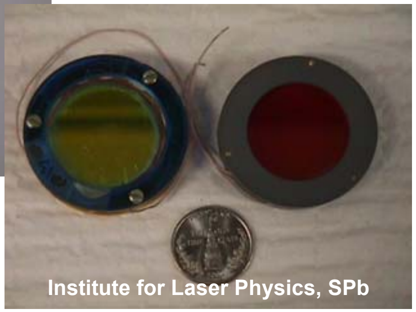
Programmable High-Resolution Phase Modulator System

following Hamamatsu Photonics K.K. product

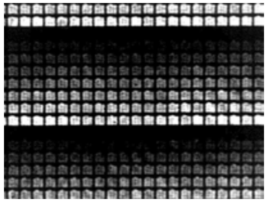
Approach: commercial EASLM / Fourier filter / customized amplitude-to-phase converter

- leverage commercial high-resolution EASLM market
- utilize Fourier filtering to optimize fill factor and influence function
- explore optical physics and system capabilities of diffractive wavefront compensation

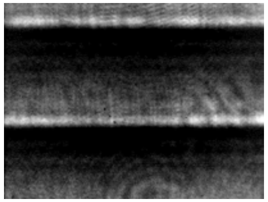




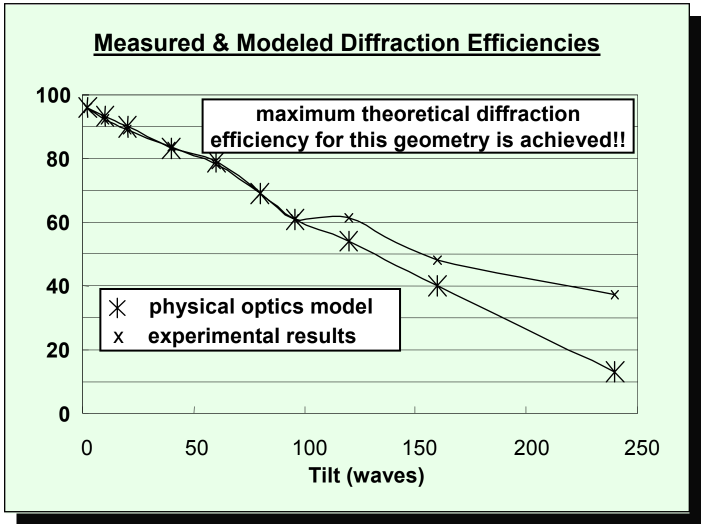
features
640 x 480 array
307,200 elements
VGA interface
>2π phase range



EASLM output
60 λ tilt mod-λ
spatial filter open

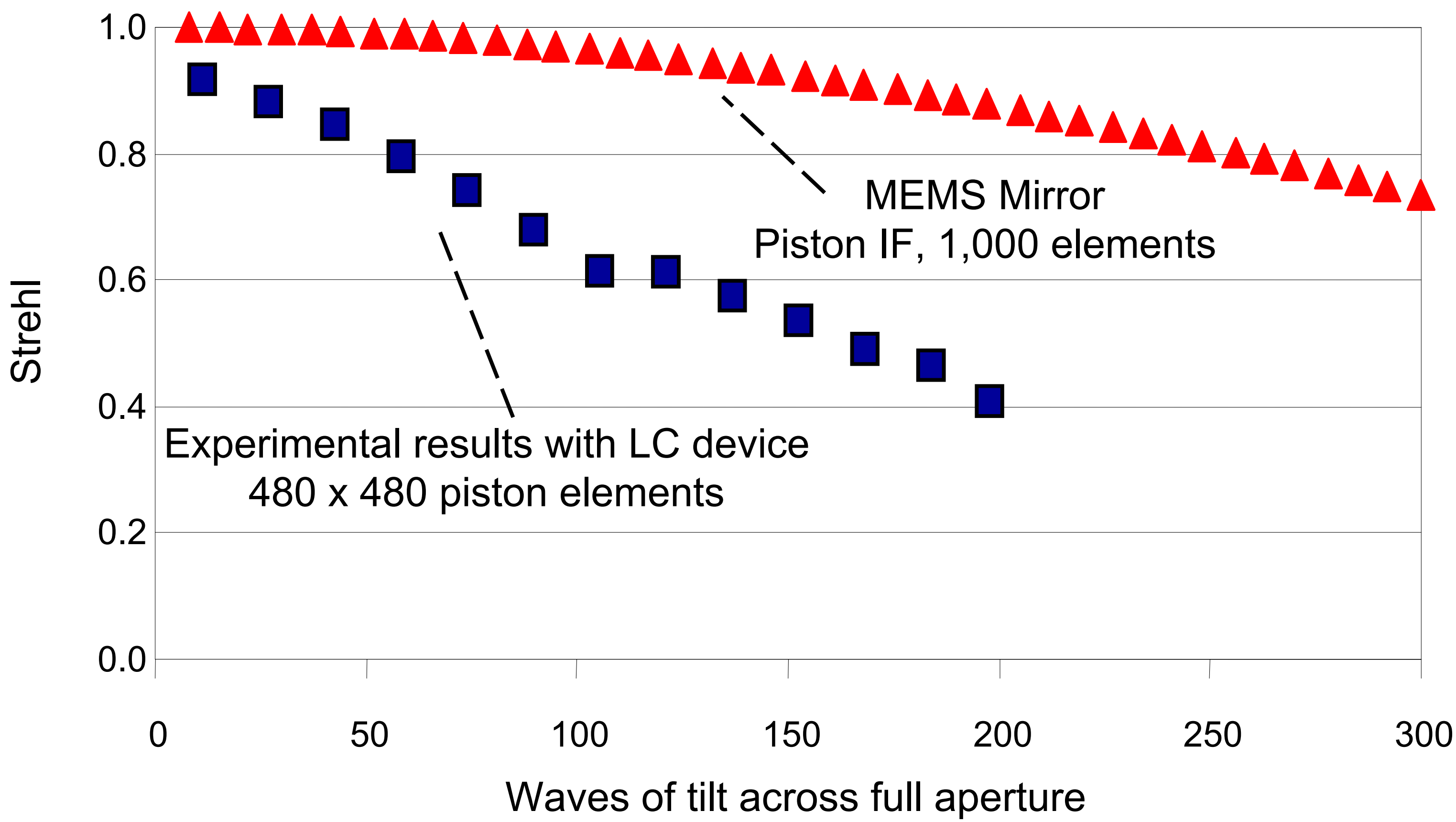


OASLM input
with spatial filtering
to remove pixelation



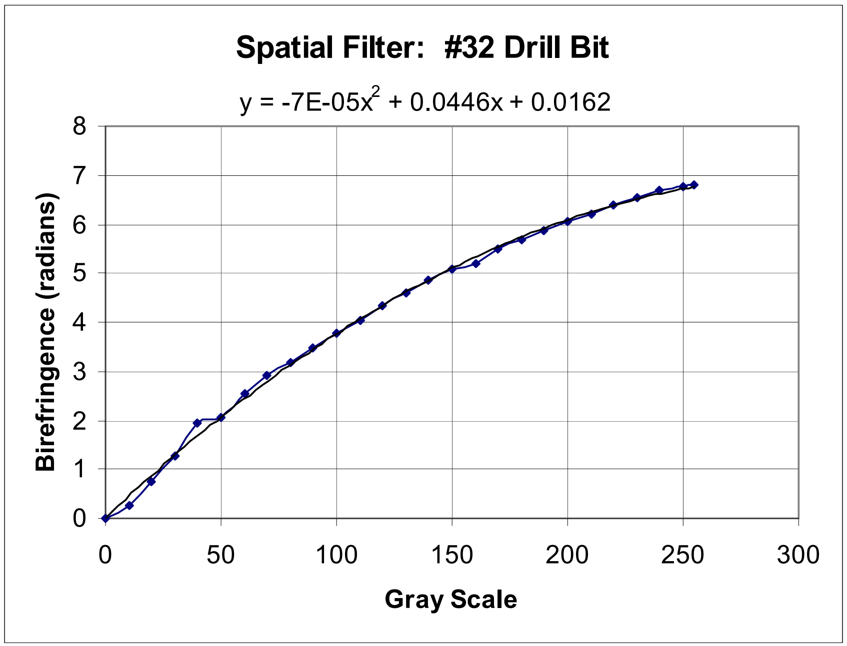
Modeled Diffraction Efficiency for MEMS Mirror

Justin Mansell, Intellite, Inc.

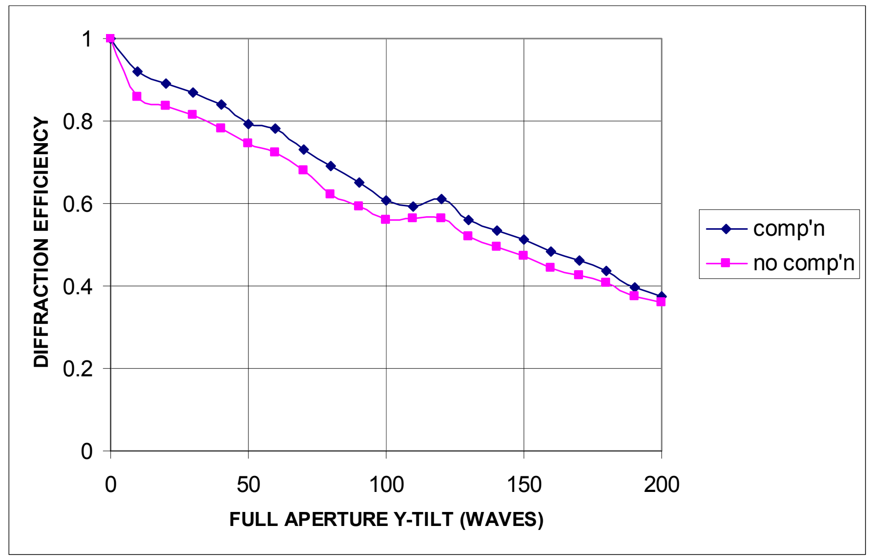


Phase Dynamic Range and Linearity with Hamamatsu Large Area OASLM

Phase dynamic range and Linearity



Diffraction Efficiency

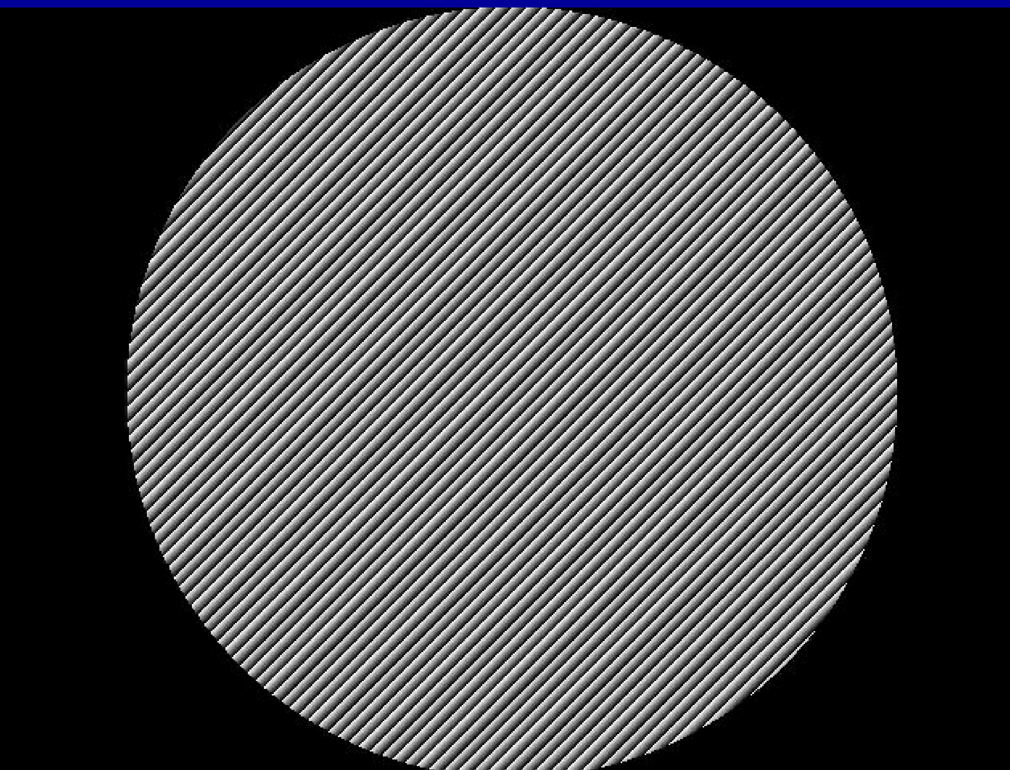


Phase response is not linear

Can compensate computationally

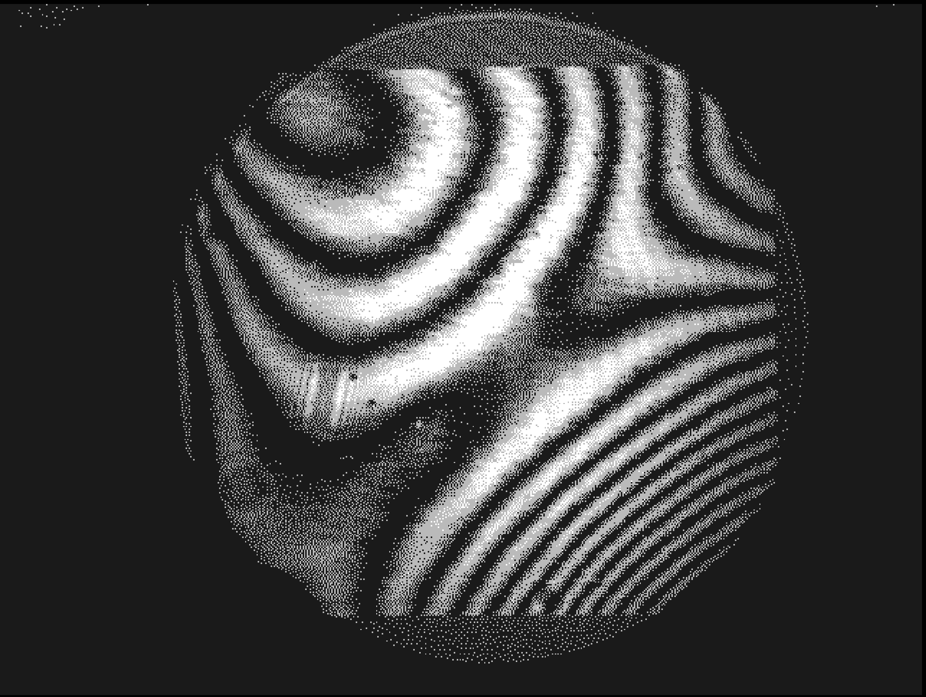
Programmable Diffractive Optics Demonstrations

Diffractive Wavefront Control - Dynamic Beam Scanning *with High Optical Efficiency*

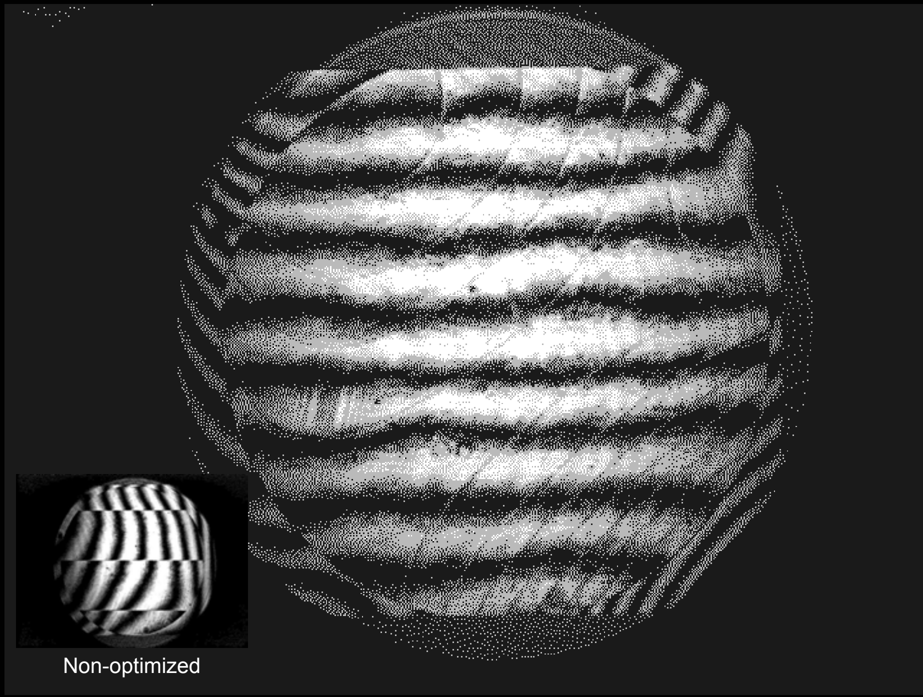


Programmable Wavefront Control Demonstration
High-Fidelity Aberration Compensation

Programmable diffractive optic



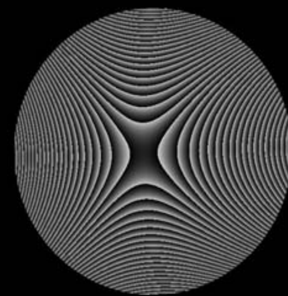
Aberrated Wavefront
10 λ aberration



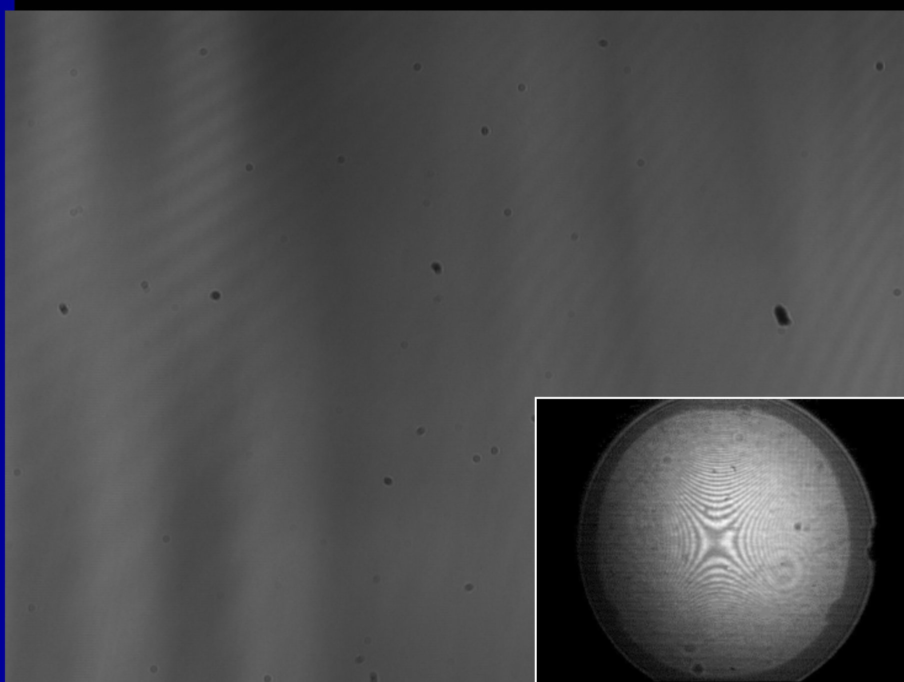
Compensated Wavefront
$\lambda/8$ residual aberration

Compensated Telescope: 10-Degree Off-Axis Aberration Compensation

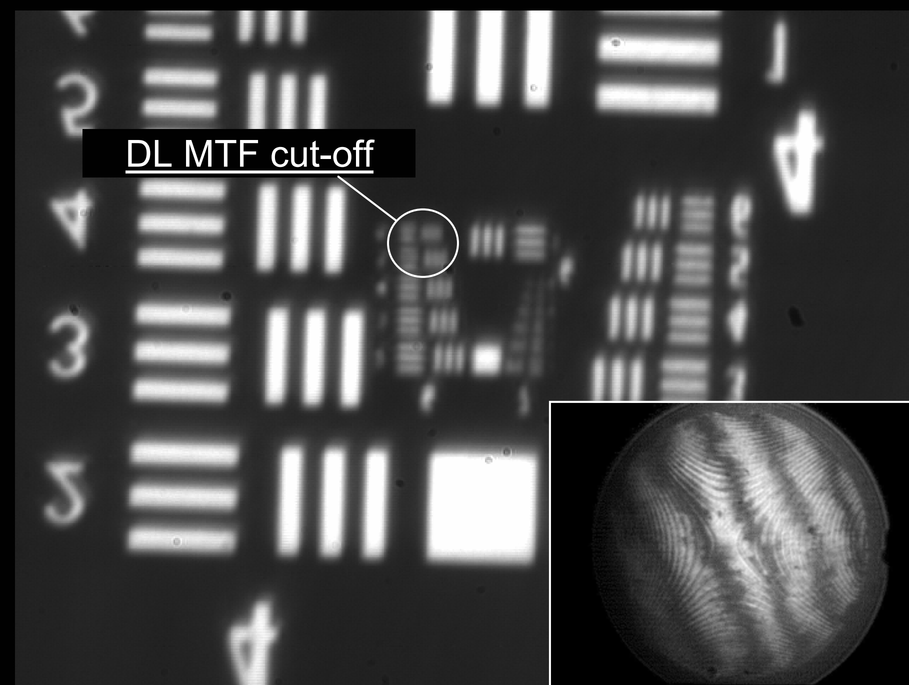
factor-of-70 increase in FOR



programmable diffractive optic phase profile



without compensation
~ 40λ p-p aberration



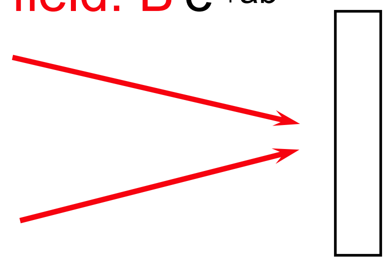
with compensation
diffraction-limited performance

2. Wavelength Dependence

Mathematics of Diffractive Phase Subtraction from Amplitude Modulation Holography

aberrated beacon field: $B\, e^{i\phi_{ab}}$

a) **write process**:



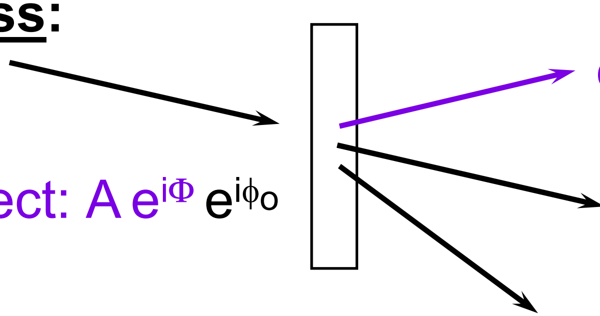
hologram {OASLM}

mutually coherent plane wave: B

hologram transmission function: $T \sim 2 + e^{i\phi_{ab}} + e^{-i\phi_{ab}}$

b) **read process**:

aberrated object: $A\, e^{i\Phi}\, e^{i\phi_o}$



$e^{i\Phi}\, e^{i(\phi_o - \phi_{ab})}$ compensated image

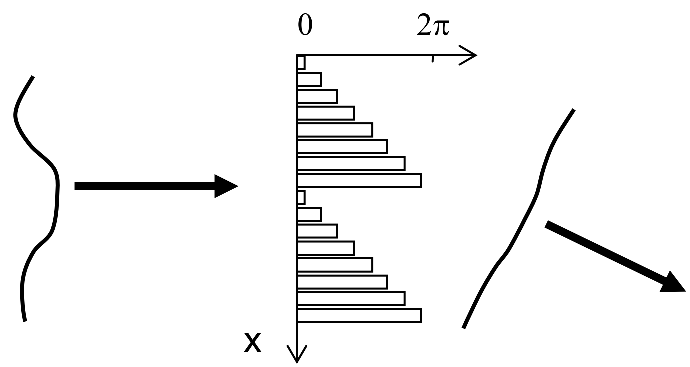
$e^{i\Phi}\, e^{i\phi_o}$ aberrated image

$e^{i\Phi}\, e^{i(\phi_o + \phi_{ab})}$ doubly aberrated image

Mathematics of Diffractive Phase Subtraction (cont.)

<u>phase profile of aberrated wavefront</u>

$\phi_{wavefront}(x,y) = (2\pi/\lambda_{wavefront})\ OPD(x,y)$



<u>phase profile associated with diffractive optic</u>

$\phi_{diffractive\ optic}(x,y) = (2\pi/\lambda_{reset})\ OPD(x,y)$

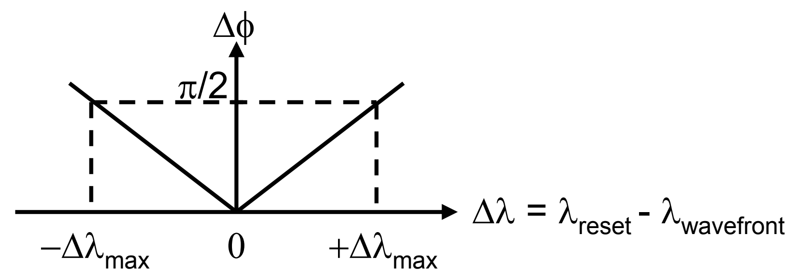
<u>phase profile of compensated wavefront</u>: $\Delta\phi(x,y) = \phi_{wavefront}(x,y) - \phi_{diffractive\ optic}(x,y)$

let $\Delta\lambda = \lambda_{reset} - \lambda_{wavefront}$, then $\Delta\phi(x,y) = (2\pi\Delta\lambda/\lambda_{reset}\lambda_{wavefront})\ OPD(x,y)$

Mathematics of Diffractive Phase Subtraction (cont.)

Residual chromatic phase error: $\Delta\phi(x,y) = (2\pi\Delta\lambda/\lambda_{reset}\,\lambda_{wavefront})\,OPD(x,y)$

Diffraction-limited requirement: $\Delta\phi < \pi/2$ {or quarter-wave peak-to-peak wavefront error}



Diffraction-limited bandwidth: $2\Delta\lambda = (\lambda_{wavefront}\,\lambda_{reset})/(2*OPD_{max})$

The maximum residual aberration occurs only over part of the aperture and part of the spectrum.

Examples

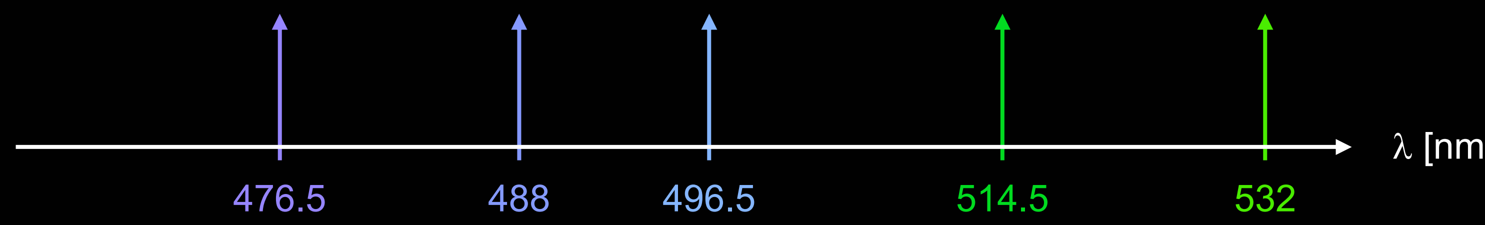
Maximum OPD	Center wavelength, λ	Diffraction Limited Bandwidth, $2\Delta\lambda$
40λ @ 550 nm	550 nm	7 nm
	1.0 μm	23 nm
	10.0 μm	2,300 nm

Compensated Telescope: Wavelength-Agile Imaging Demonstrations

wavelength scaling of diffractive optic

compensated images with 40-λ p-p aberration @ 10-degree field angle

Illumination laser lines

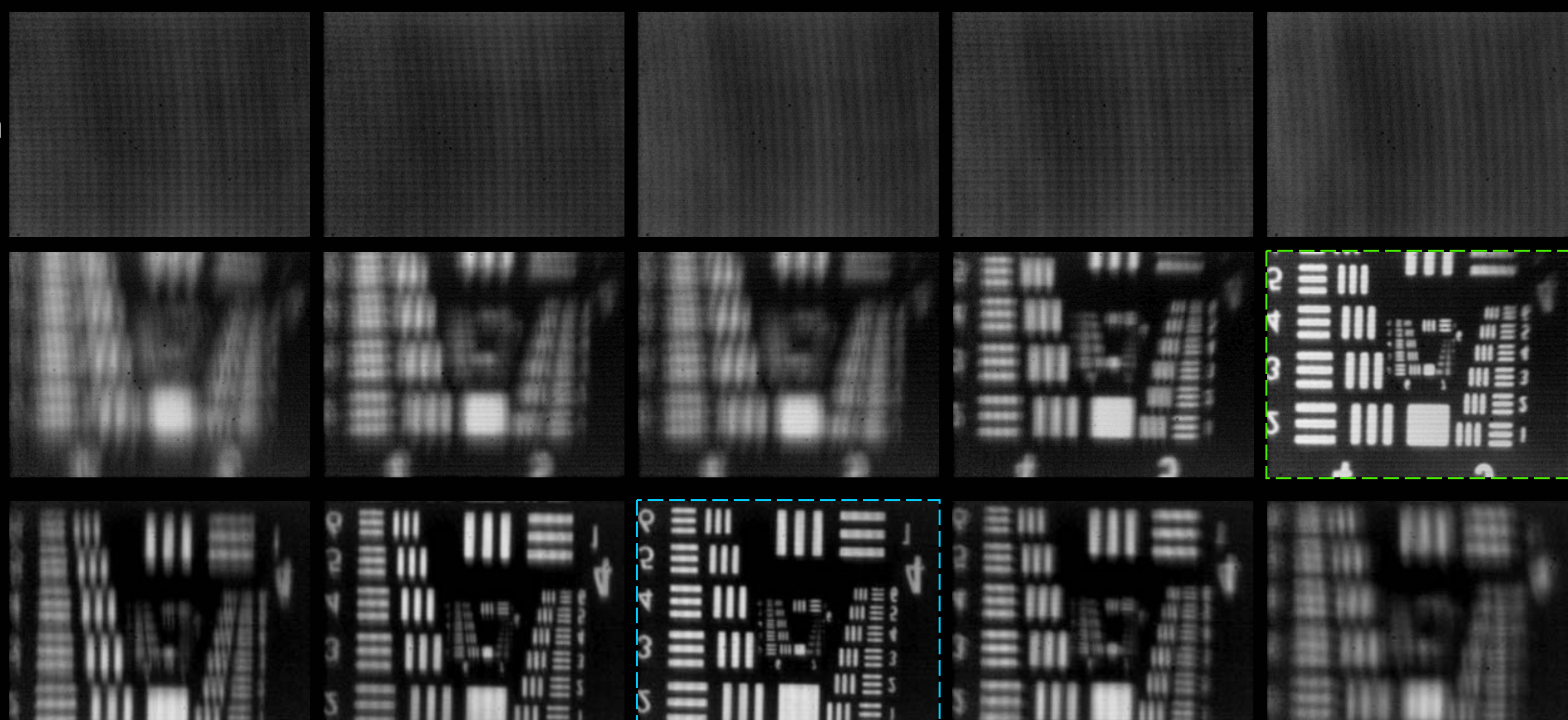


wavelength [nm] 476.5 488 496.5 514.5 532

no compensation

compensation @532 nm

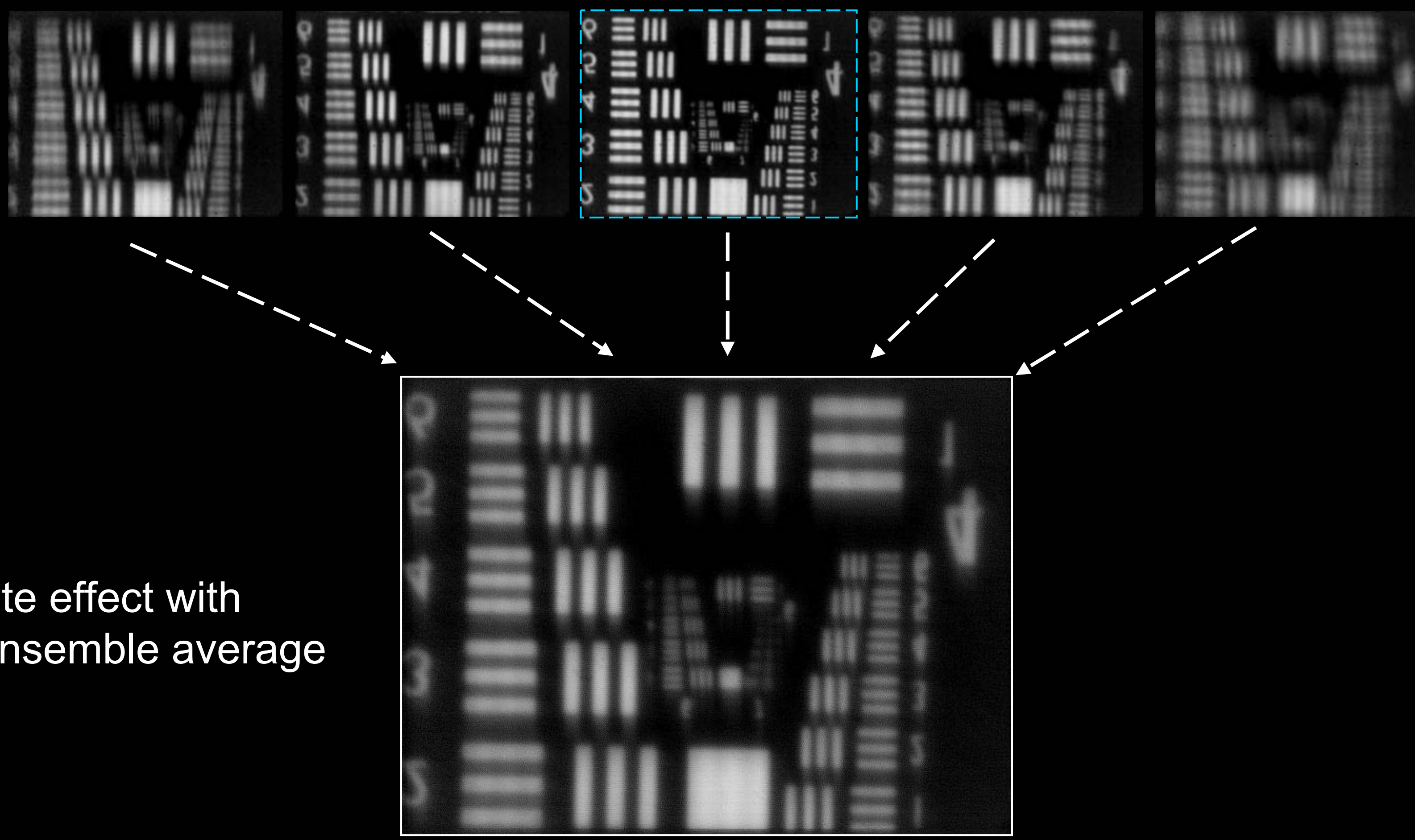
compensation @504 nm



What about extended spectral bandwidths?

wavelength [nm] 476.5 488 496.5 514.5 532

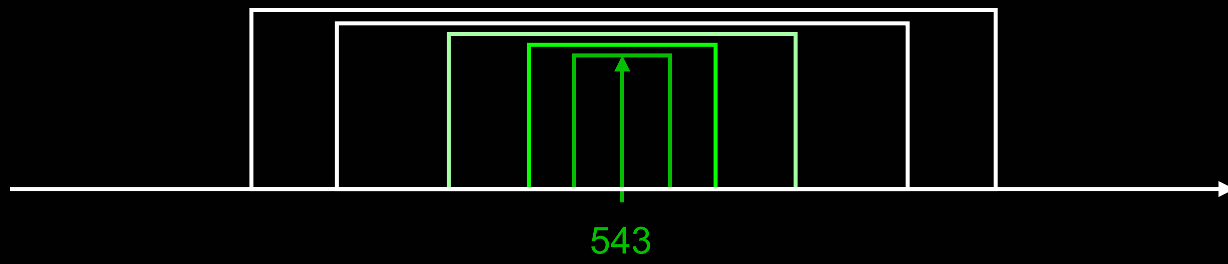
compensation @504 nm



estimate effect with
multi-line ensemble average

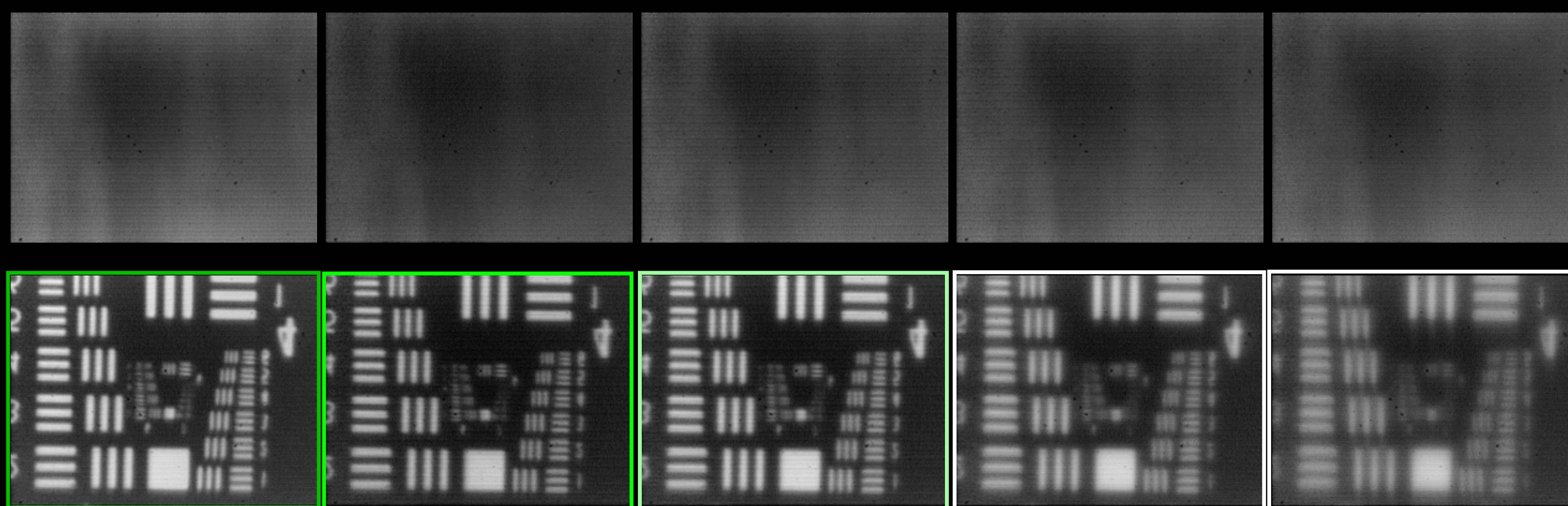
Passive Illumination Imaging Demonstration

Accomplishment: identified spectral bandwidth limitation



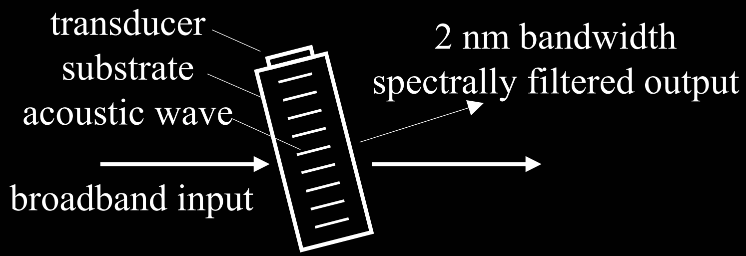
Spectral Filter Bandwidth FWHM

	10 nm	30 nm	50 nm	100 nm	no filter
compensation OFF					
compensation ON					



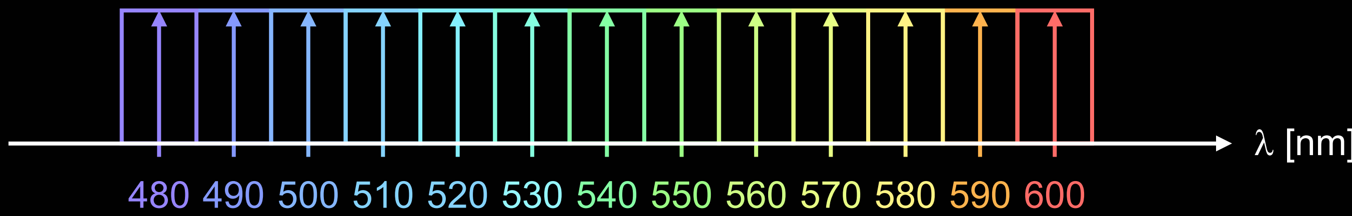
Resolution Cutoff Group-Element:	6-4	6-3	6-3	6-3	6-1

← near-diffraction-limited resolution →



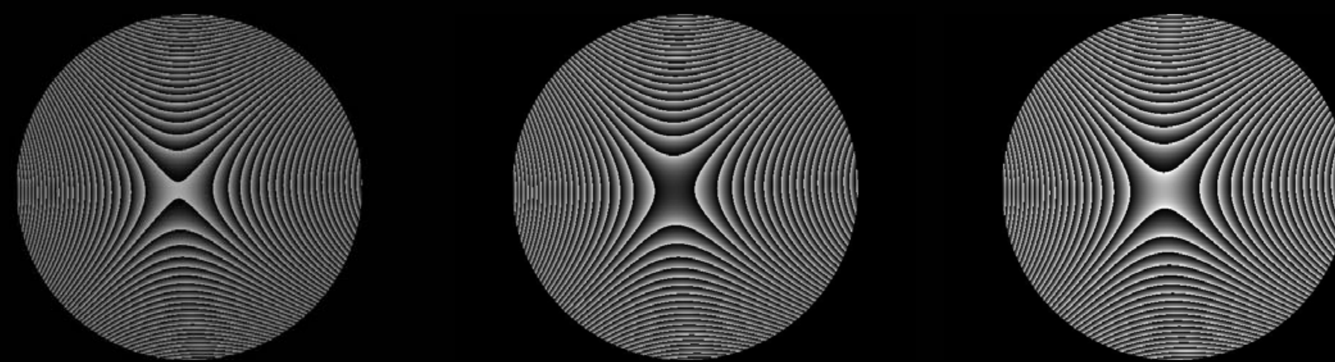
Tunable Spectral Filter Demonstration

NMSU/NASA –Prof. David Voelz & Melinda Deramo

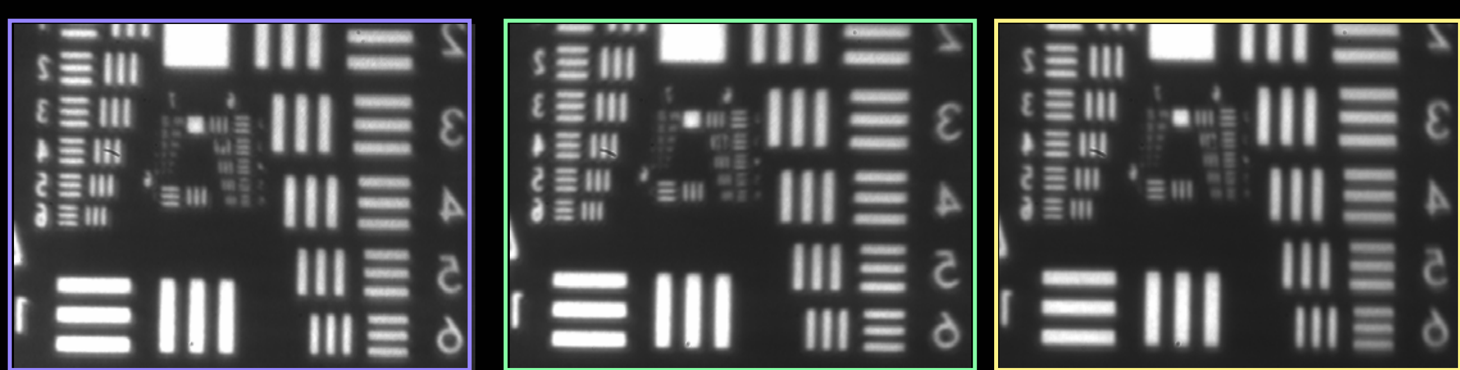


center Wavelength [nm] 480 540 580

phase compensation profile



Near-diffraction-limited compensated images



Conclusions

- Significant performance capabilities have been demonstrated with a prototype programmable diffractive optics setup.
  - high optical efficiency
  - large aberration compensation with nearly diffraction-limited performance
  - wavelength tunability
  - extended spectral bandwidth operation

- Liquid-crystal technology faces some challenges
  - response time
  - absorption may limit optical power levels
  - polarization dependence can affect net efficiency

- Alternate technologies that may advance the capabilities of Programmable Diffractive Optics
  - high-resolution MEMS (micromachined electro-mechanical systems) Mirrors

The five enabling Technologies

- Advanced WFC*
- Agile narrowband filters (NMSU)
- Wide Dynamic range WFS* (UAH?)
- Ultra-lightweight optics (including optical windows)*
- High Altitude Airship HAA (MDA) or others

* DE developed technologies

The five enabling Technologies

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*** DE developed technologies**

Ultra-lightweight optics

- **Membrane Development**
- Membrane Mechanics
- Boundary Development
- Coatings Development

Ultra-Lightweight Polymer Membrane Mirror Technology Development

Presented by Brian Patrick

Overview

- High Technology Programs Driving Membrane Research
- Polymer Material for Membrane Optical Elements
- Requirements for Imaging Applications
- Current Research Progress for Flat and Curved Membranes
- Conclusions

Program Goals Driving Membrane Optics Research

Space Science Goals

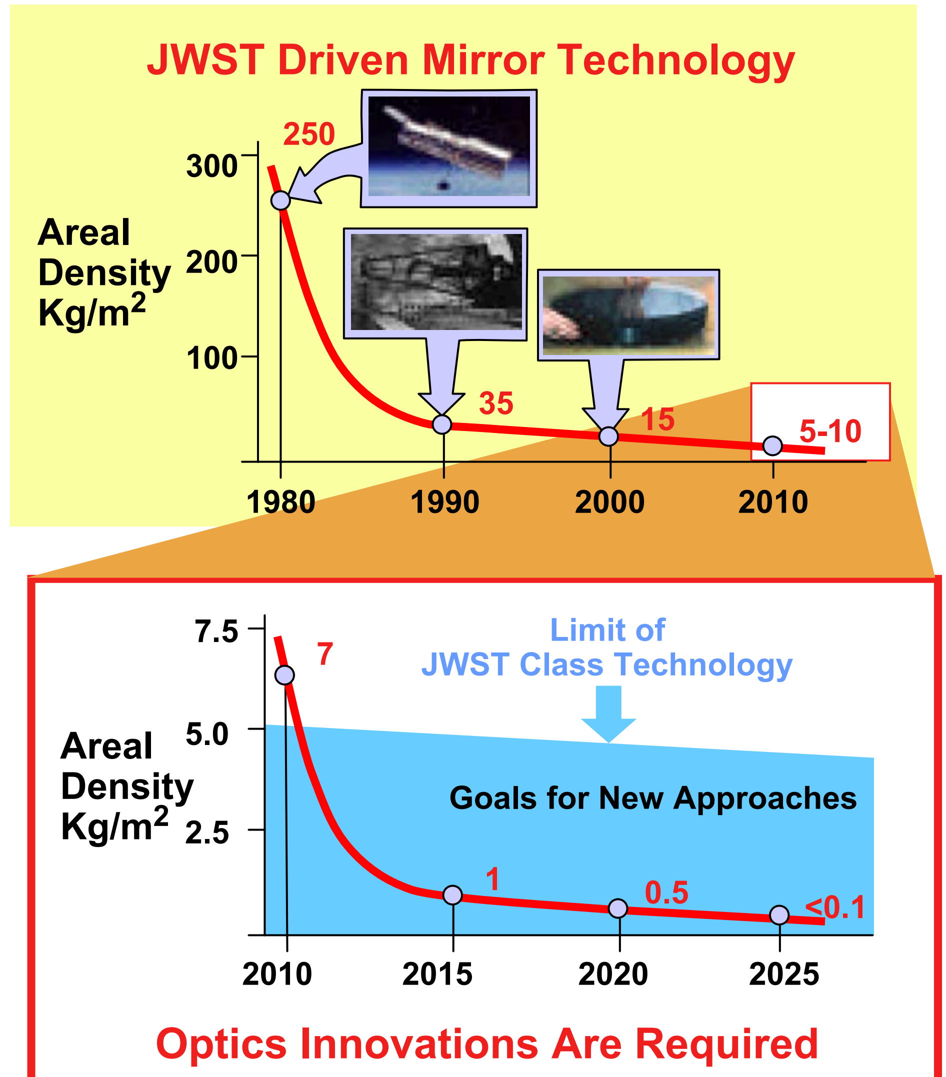
- JWST Space Telescope 50m^2 (6 m Aperture)
- Planet Spectroscopy >1,000 m^2 (40 m Aperture)
- Planet Imaging >25,000 m^2 (200 m Aperture)

Earth Science

- IR Imaging
- Resource Mapping
- Passive Microwave Imaging
- Sensor Locations Beyond LEO

DOD

- Reconnaissance
- Directed Energy
- Radar
- Communications



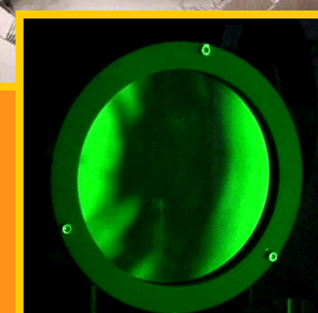
Reference: Rich Capp's "Ultra Lightweight Space Optics Challenge Workshop"

Membrane Material for Optical Applications

CP1™ (Clear Polyimide)

- Developed by NASA Langley specifically for Space Applications
- Material Synthesized by SRS Under Exclusive License from NASA. (End to End Quality Control)
- Film Manufacturing Process Results in Very Homogenous Film Properties
- Wide Range of Operating Temperatures (Cryogenic - 250C)
- Resistant to UV Radiation
- Film Solubility Enables Advanced Casting and Surface Replication Manufacturing Techniques

In-House Polymer Manufacturing Facilities



Thin-Film Polymer Technology Heritage

- **15+ Years Experience in Research and Development of Polyimides and Polyimide-Based Thin-Film Structures**
- **Research Began in the Development of Thin-Film Reflectors Used for Solar Concentrators and RF Antennas**
    - **Polyimide Production Development**
    - **Fabrication and Characterization of Polyimide Thin Films**
    - **Development of Innovative Applications for Thin-Film Structures**
- **Figure and Surface Error Tolerances for Non-Imaging Applications Were Easily Achieved.**

Background and Challenges for Membrane Optics

RMS Wavefront Error	$1\text{-}5\times10^{-3}$ meter	$<1\times10^{-3}$ meter	$\sim150\times10^{-9}$ meter
RMS Slope Error	0.5mm at X Band	$\sim2\times10^{-3}$ Radian	$\sim1\times10^{-6}$ Radian
RMS Thickness Variation	NA	NA	$\sim75\times10^{-9}$ Meter
Conductivity (A Few Skin Depths)	High	NA	NA
Optical Reflecting	NA	High	High

Increasing Difficulty

1	10	1000

Primary Requirements for Precision Membrane Optics

Surface Finish

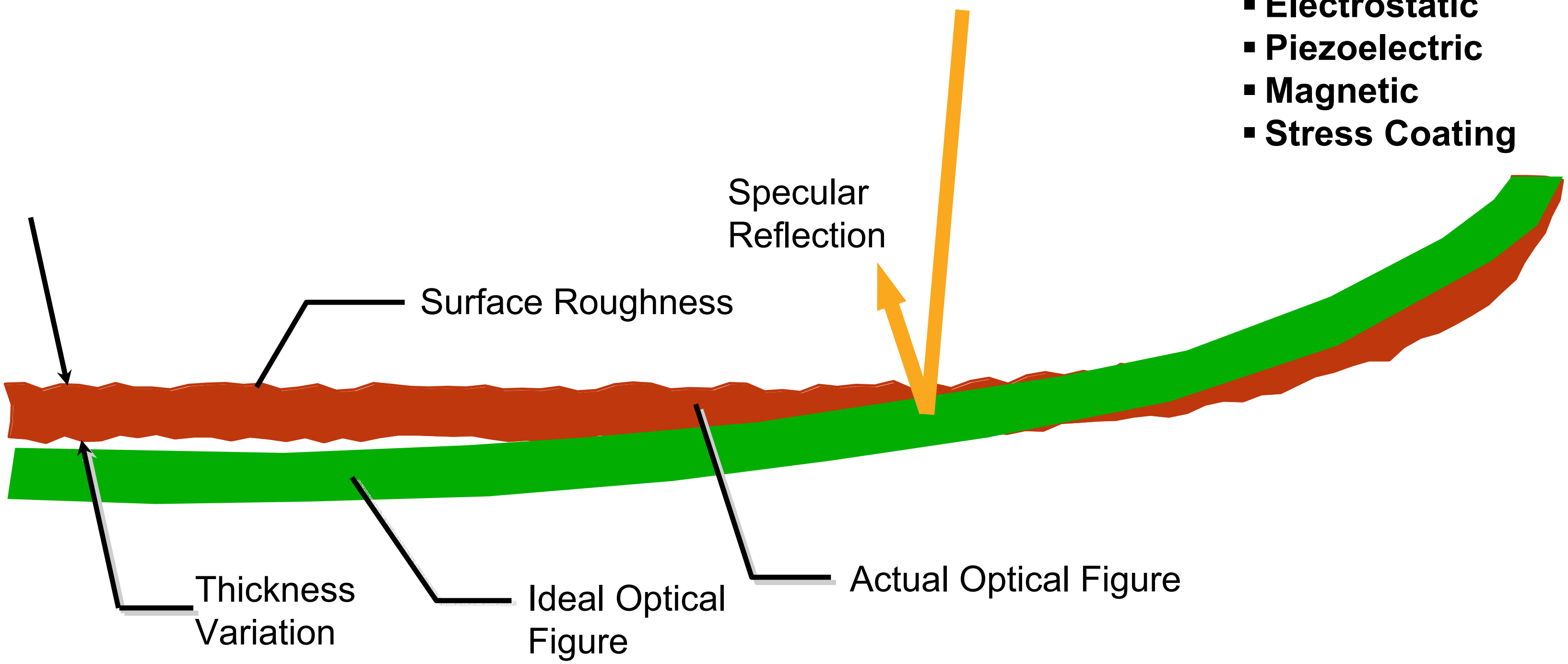
- A Highly Polished Specular Surface is Required to Transmit or Reflect Incident Light With Minimal Wave Front Distortion

Uniform Thickness

- Thickness Variations will Contribute to Figure Errors
- Stressed Membranes Assume the Figure of the Mid Plane

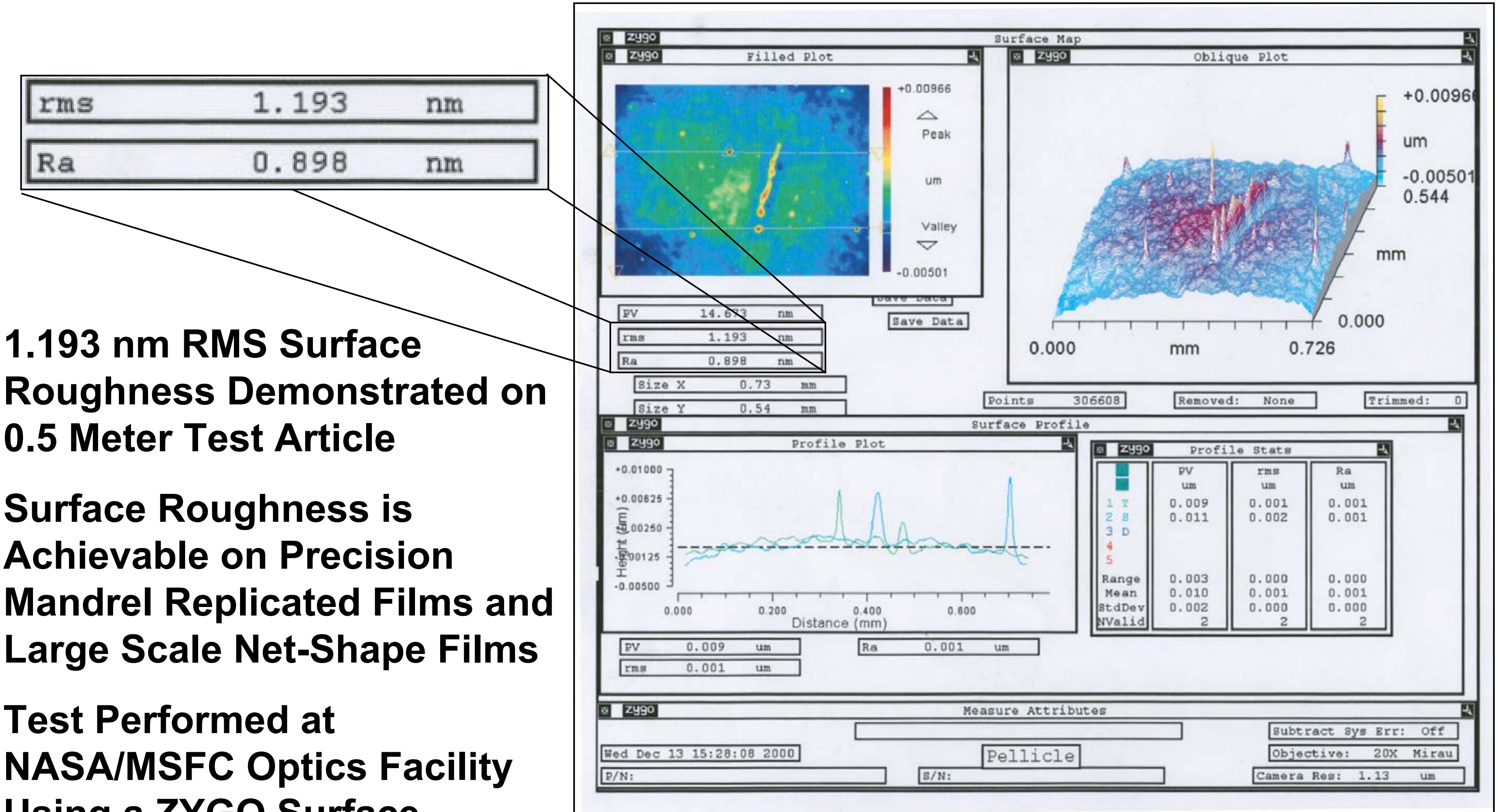
Figure Control

- Boundary Control
  - Rigid Ring
  - Compliant Ring
  - Active Tuning
- Global Shape
  - Shape Memory
  - Electrostatic
  - Piezoelectric
  - Magnetic
  - Stress Coating



Surface Roughness for SRS CP1™ Cast Membrane Films

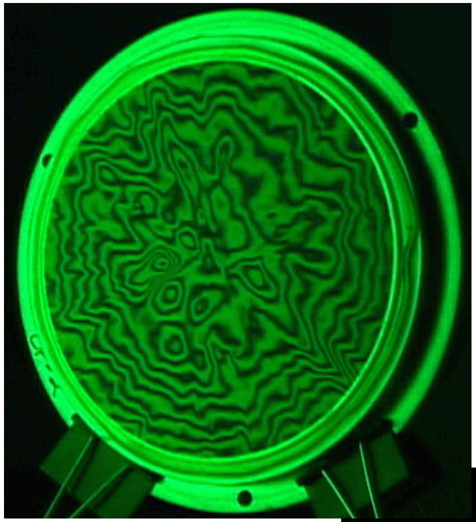
- 1.193 nm RMS Surface Roughness Demonstrated on 0.5 Meter Test Article
- Surface Roughness is Achievable on Precision Mandrel Replicated Films and Large Scale Net-Shape Films
- Test Performed at NASA/MSFC Optics Facility Using a ZYGO Surface Roughness Interferometer



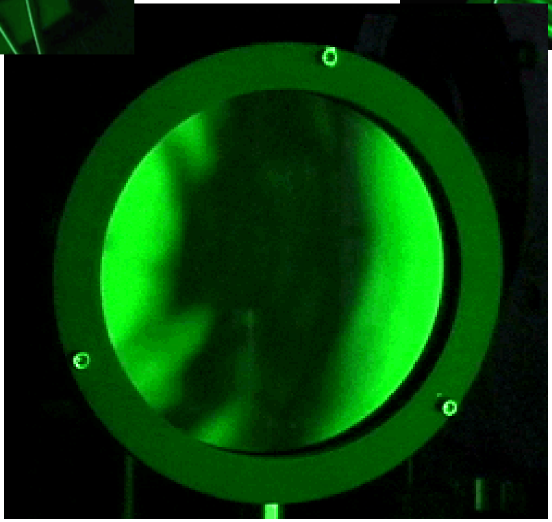
Surface Topography for SRS CP1™ Sample Cast from a Non-Precision Float Glass Substrate

Membrane Thickness Variation Process Refinement

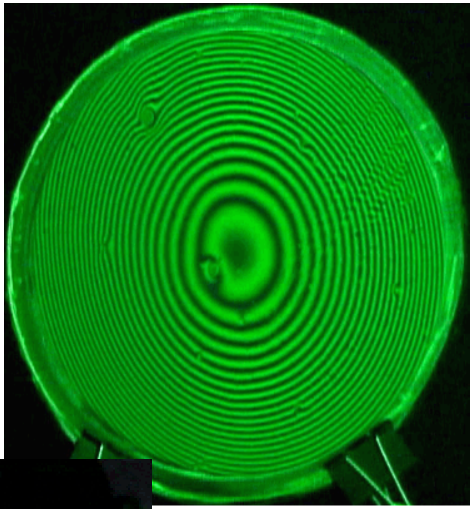
- Modifications to Casting Process Has Resulted in Drastic Improvement in Thickness Variation Present on Both Flat and Curved Substrates.
- Sub-Wavelength Thickness Variation Demonstrated on Apertures Up To 0.5-Meters.



Typical Membrane Material

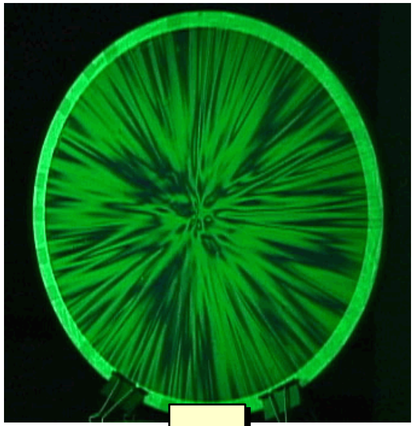


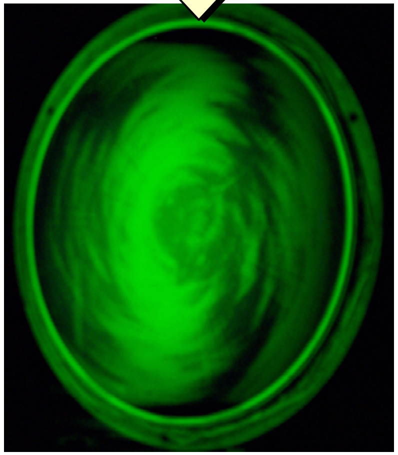
Minimized Thickness Variation



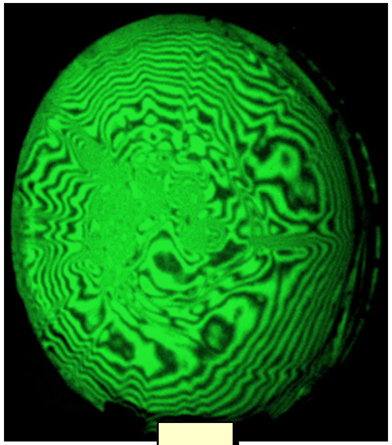
Uniform Thickness Variation

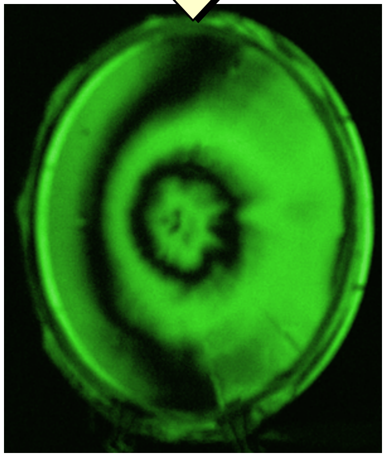
Membrane Thickness Variation Process Refinement for Curved Substrates





Thickness Variation Reduction on Convex Spherical Mirror, 0.5-Meter Diameter with f/1.87

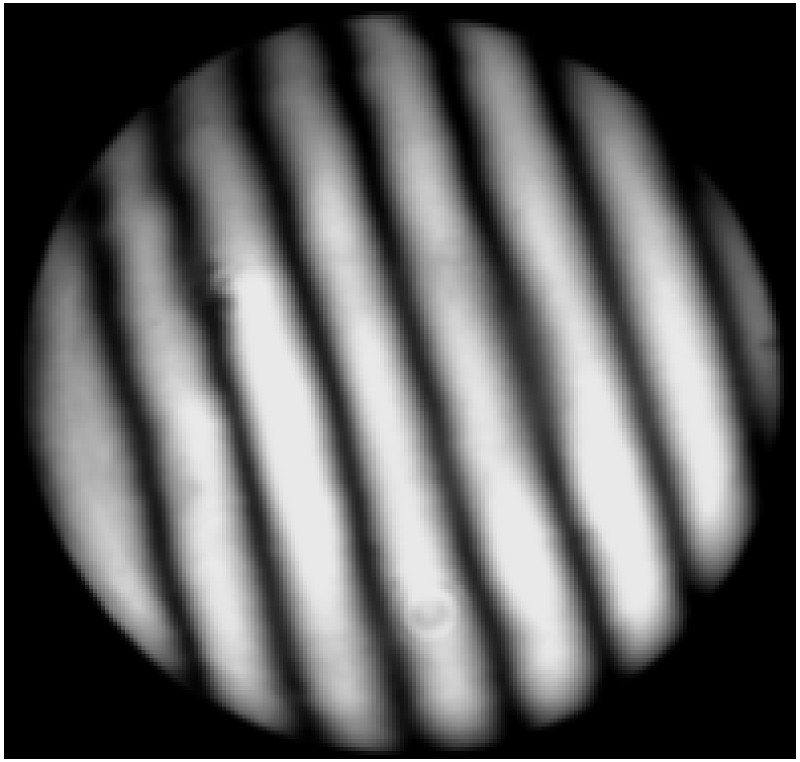




Thickness Variation Reduction on Concave Parabolic Mirror, 0.3-Meter Diameter with f/4.6

Fizeau Fringes from Thickness Variations

Extreme Minimization of Membrane Thickness Variation



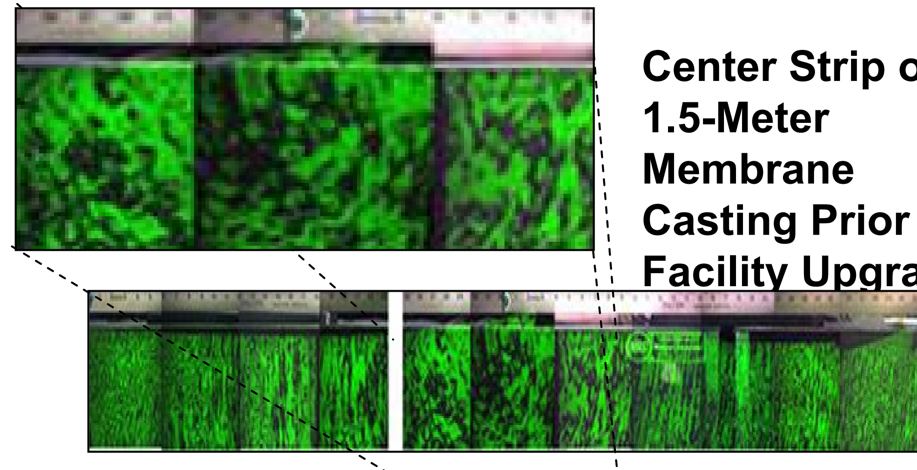
Courtesy AFRL DÈ

- Double-pass Interferogram of a 10cm Sample of CP-1
- Thickness Uniformity ~1/20 Wave rms

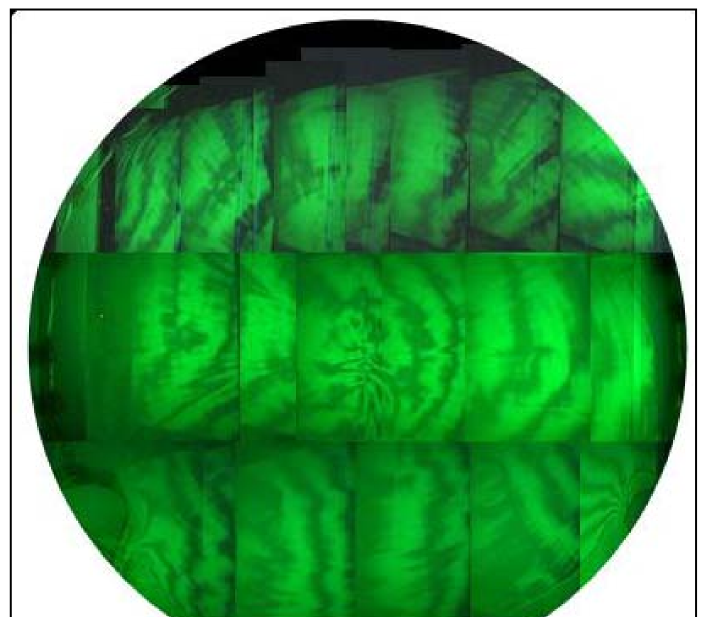
Fizeau Fringes from Thickness Variations

SRS Large-Scale Casting System

- New Large-scale Membrane Facility Has Been Installed at SRS and Initial Castings Have Shown Similar Success in Thickness Variation. Expandable up to 3-Meter Diameter Castings.
- Currently Thickness Variation Has Been Minimized to ~2 Waves of Error Over 1.5-Meters.



Center Strip of 1.5-Meter Membrane Casting Prior to Facility Upgrade

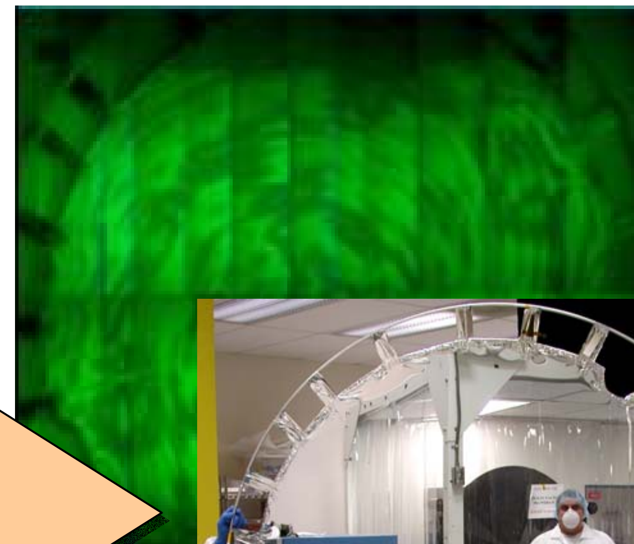


Thickness Variation Composite of 1.5-Meter Diameter CP-1 Membrane Revealing Only ~2 Waves of Error.

SRS Large-Scale Casting System

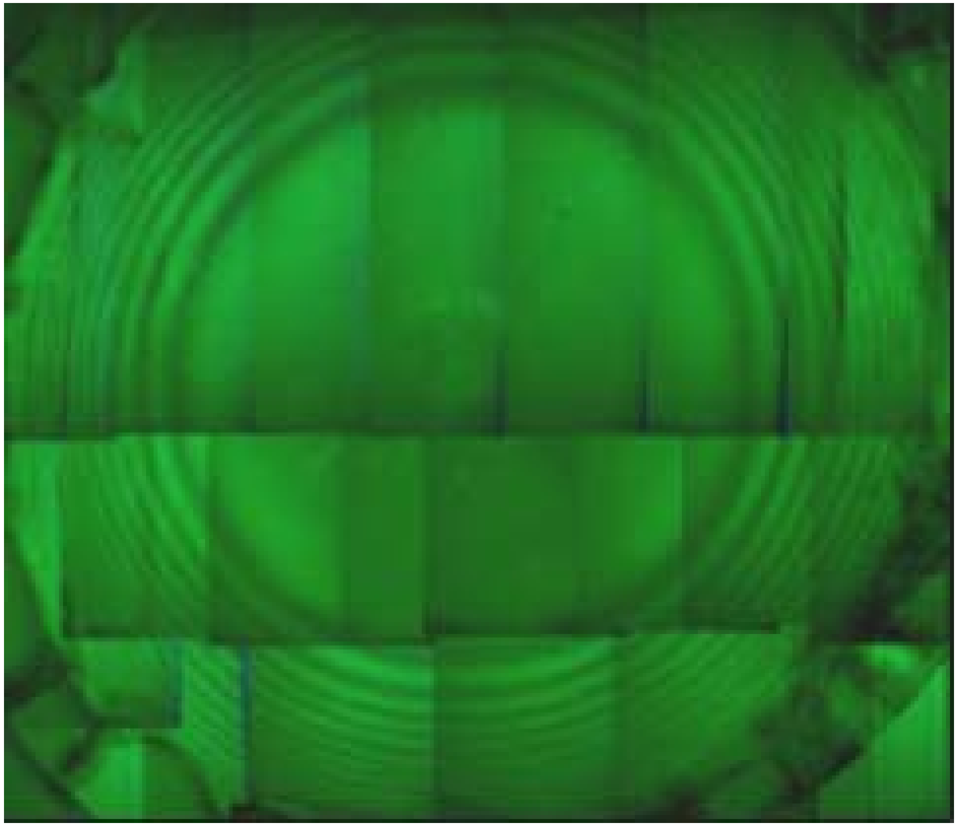
SRS Has Shown Precision Membrane Production Using a Custom Manufactured Large-scale Casting System.

- **1.5-Meter Membrane Flats Manufactured Have Been Successfully Coated.**



SRS Large-Scale Casting System

- Further Process Development of 1.5-meter Membranes Has Resulted in Essential Null Fringe Thickness Variation Over Approximate 1-Meter Central Diameter.
- Currently This Has Been Achieved on Very Thin Films (~5-micron)
    - Additional Research Can Increase This Thickness.

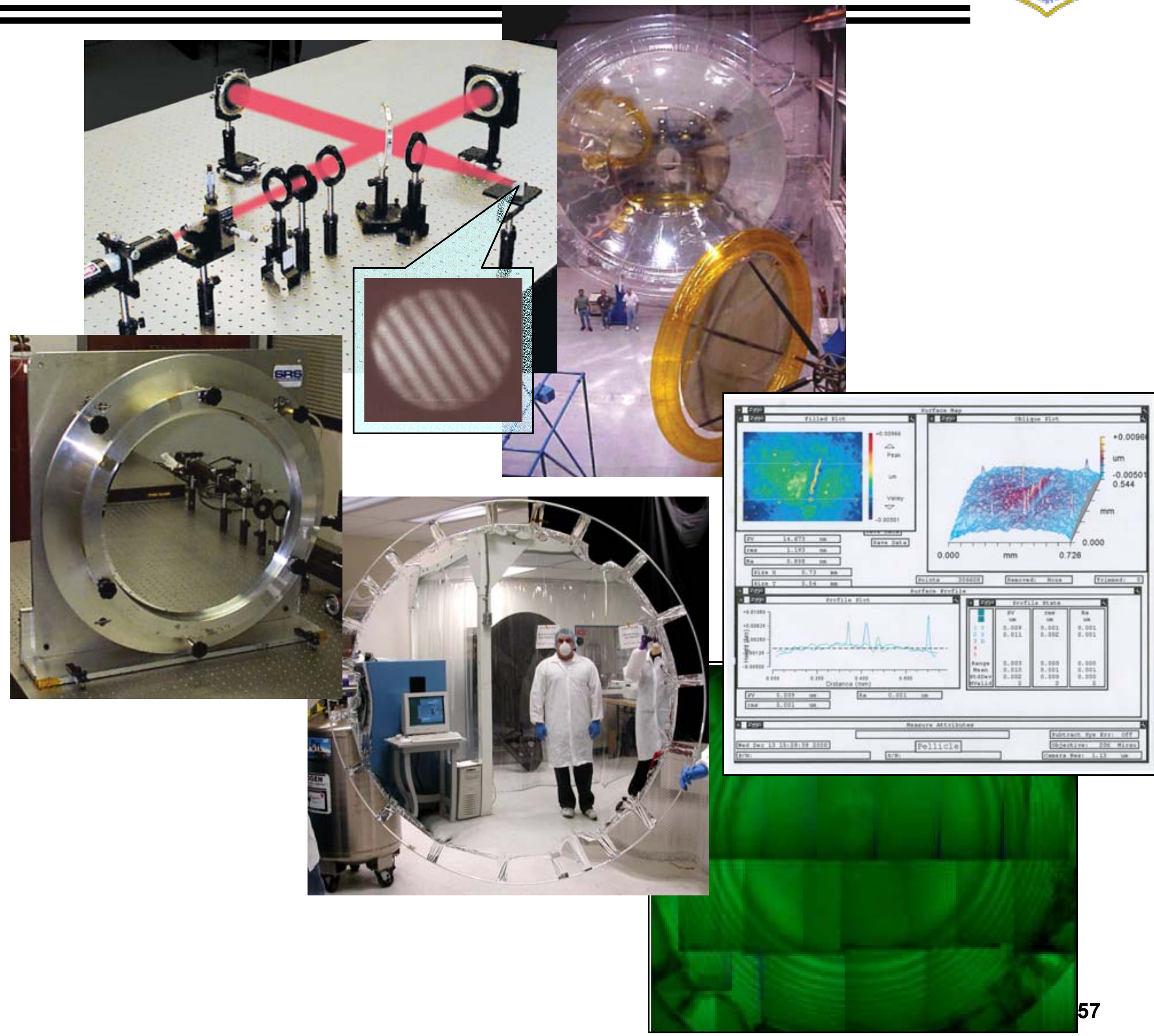


Conclusions

- Membrane Optical Elements, With Areal Density of 0.05 kg/m^2 (Unsupported), Have Been Manufactured With Surface Finish and Thickness Tolerance Sufficient for Precision Optical Applications
- Practical Flat Membrane Elements Are Available Now. Additional Research Is Under way to Further Address Lightweight Support and Figure Control for Curved Optical Elements.
- Scaling Technology Exists to Create Very Large Aperture Membrane Elements.
- Candidate Applications Include Antenna, Solar Power, as well as Imaging

Membrane Mirror Technology

- Such Membrane Technology Has Led to Expanded Research for Using Them As First Surface Mirrors
- Optical Quality Membranes Can Be Manufactured up to 1.5-Meters in Diameter. Expandable up to 3-Meters



Ultra-lightweight optics

- Membrane Development
- **Membrane Mechanics**
- Boundary Development
- Coatings Development

Membrane Mechanics: MANS

Christopher H. M. Jenkins

Compliant Structures Laboratory

Mechanical Engineering Department

S. D. School of Mines and Technology,Rapid City, SD

James M. Wilkes

Air Force Research Laboratory

Directed Energy Directorate

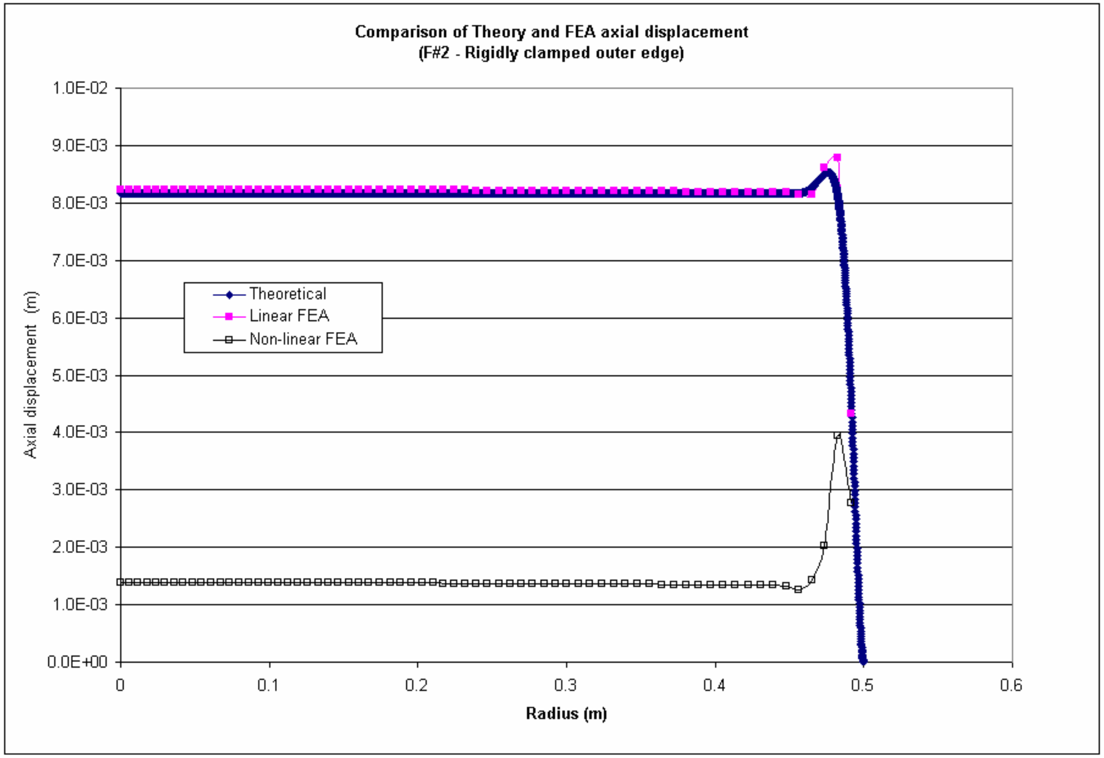
Kirtland Air force Base, NM

Introduction

- Membranes are inherently *under-constrained* structures that rely on prestressing, e.g., by inflation, for in-plane compression or out-of-plane stiffness
- Use of stress inherent in optical coatings provides a unique opportunity for figuring the membrane aperture

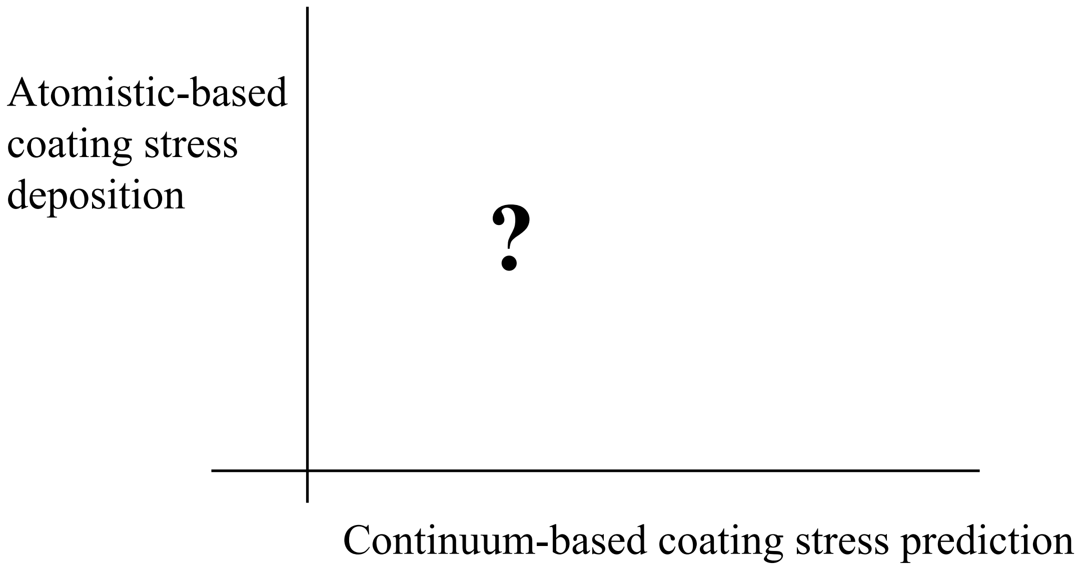
The Continuum-Based Models

- Two kinds of continuum-based models have been developed to prescribe the coating stress required to figure the membrane mirror:
  - Theoretical models developed by Dr. Wilkes, AFRL/DEBS
  - Nonlinear FE models developed at the Compliant Structures Laboratory
- Within the range of applicability of the theory, both models have been shown to be in good agreement



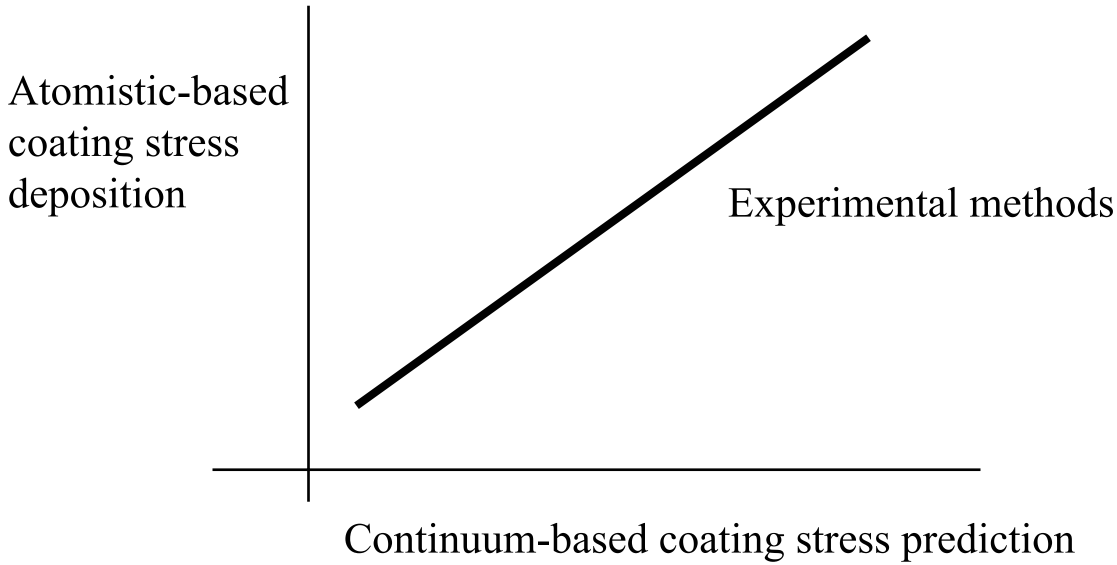
A Length-Scales Problem

- **There is a huge gap, however, between continuum-based model prescriptions of coating stress requirements and atomistic processes for applying the coating stress**



Bridging the Length-Scales

- **Other work has proceeded to provide a “calibration” between the continuum-based models and atomistic-based processes**



Bridging the Length Scales

- **Measurement of the coating stress applied may potentially be accomplished by one or more of several methods, chief among these being:**
  - **curvature measurement**
  - bulge test
  - **x-ray diffraction**
- **Several other techniques may also prove useful as stress measuring techniques in themselves, or as adjuncts to the stress characterization:**
  - vibration testing
  - **Raman spectroscopy**
  - **scanning-probe microscopy**
  - **dynamic mechanical analysis**

Comparison

- **A comparison of FE model-derived coating stress from bulge test and vibration test on a membrane coupon is given below:**

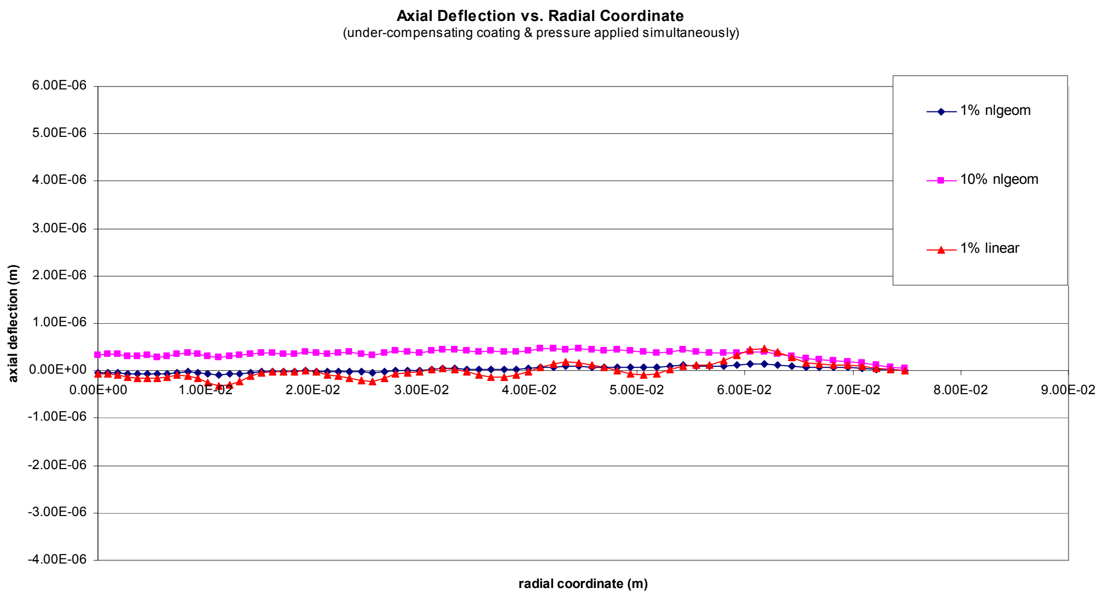
	Bulge test	Vibration test	Average
Coating stress (GPa)	1.12	1.31	1.21

Pressure Augmentation

- There are a number of good reasons why adding a small amount of pressure to the net-shape membrane is desirable.
- For one, pressure augmentation can relax the requirement on the coating prescription and application.
- Several questions then arise, for example, given an under-compensated (under-coated) membrane, what figure is achieved under pressurization?

Pressure Augmentation

- **Investigations to answer these questions are on-going**



FE results for axial displacement of under-compensated pressure-augmented MANS

Ultra-lightweight optics

- Membrane Development
- Membrane Mechanics
- **Boundary Development**
- Coatings Development

Boundary Development: MANS

Christopher H. M. Jenkins

Compliant Structures Laboratory

Mechanical Engineering Department

S. D. School of Mines and Technology,Rapid City, SD

James M. Wilkes

Air Force Research Laboratory

Directed Energy Directorate

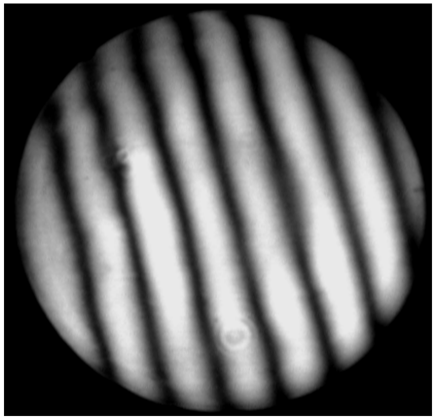
Kirtland Air force Base, NM

Introduction

Every optic needs a boundary:

- The boundary must perform many functions including maintenance (passive and/or active) of optical figure under a variety of disturbances, connection to the rest of the optical train, assisting in launch survivability, etc.

Pressure Augmented Membrane Mirror
(including optical window)



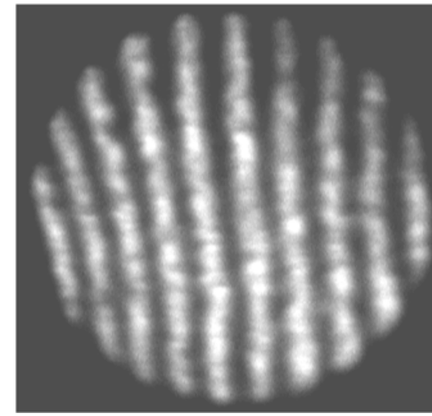
Thickness variation (rms) @ 633 nm

$\lambda/20$ @ 10 cm dia

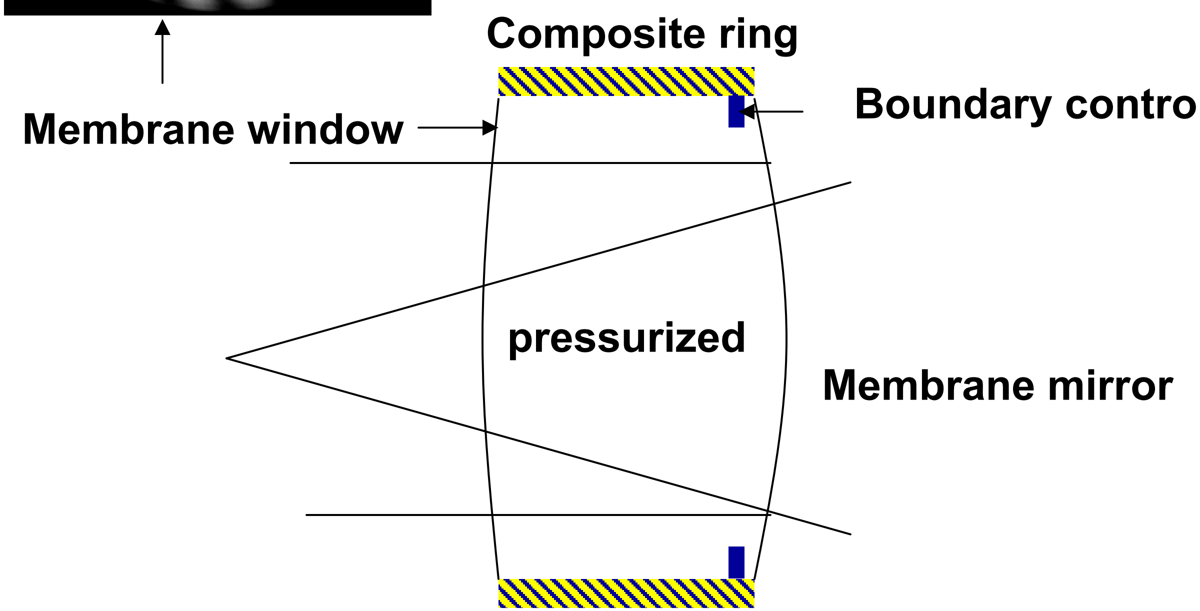
$\lambda/8$ @ 28 cm dia

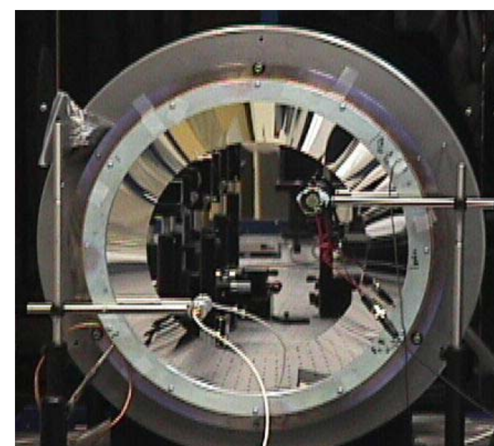
$\lambda/20$ @ 90+ cm dia

Surface roughness < 1 nm rms



$\lambda/5$ at 15 cm dia





Notional Boundary : A first look

A preliminary boundary for the MANS membrane mirror was designed based on the following requirements:

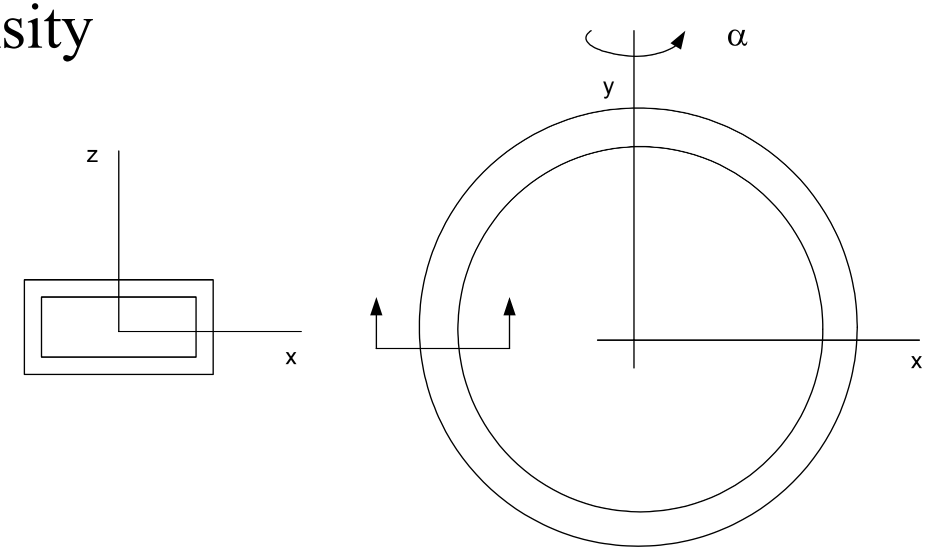
<u>For a 1 m diameter (say f/2) MANS:</u>

- Out of plane deflection $\leq 100\ \mu m$ under a slew acceleration of $0.01 - 0.1\ rad/s^2$ about a ring diameter
- Areal density $\leq 1\ kg/m^2$
- (Keep lowest natural frequency > 100 Hz)

Approach

<u>For a simple thin-walled rectangular ring cross-section:</u>

- Use ABAQUS non-linear finite element code
- Baseline aluminum and trade maximum slew deflection vs. areal density
- Baseline aluminum and trade lowest natural frequency vs. areal density



Results

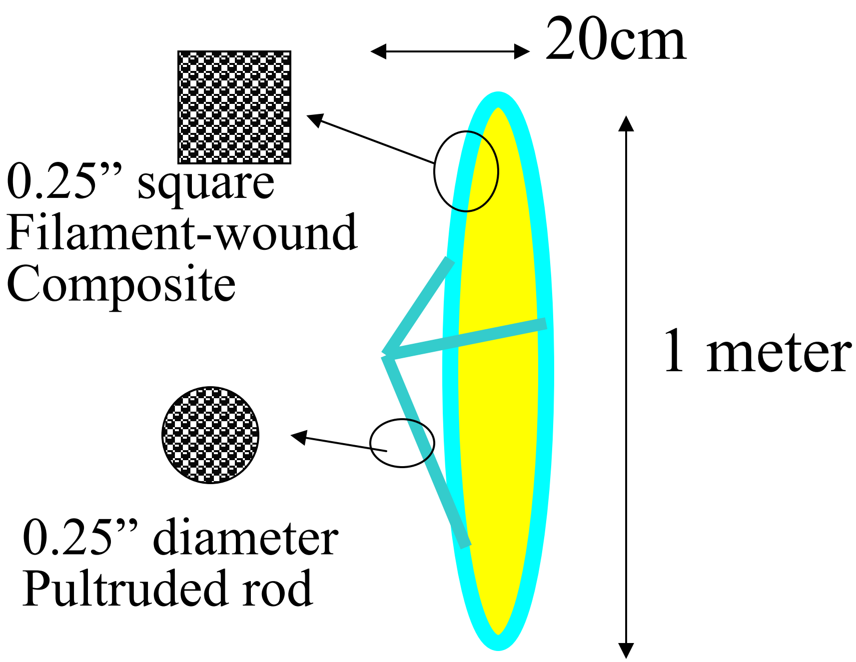
(Wall thickness = 3 mm)		α = 0.01 rad/s^2		α = 0.1 rad/s^2	
Cross-section (mm)	Areal Density (kg/m^2)	w_{max} (µm)	f_0 (Hz)	w_{max} (µm)	f_0 (Hz)
13 X 25	2.0736	2.38	20.93	23.86	20.93
10 X 25	1.8792	4.55	15.158	45.50	15.158
7 X 25	1.6848	12.90	8.9991	129.0	8.9991
13 X 13	1.296	2.95	18.828	29.59	18.828
7 X 13	**0.9072**	**14.46**	**8.4883**	**144.7**	**8.4883**

Bold font indicates design that meets areal density requirement

Further Light-Weighting

- For graphite /epoxy composite with elastic modulus = 173 GPa and density = 1500 kg/m^3

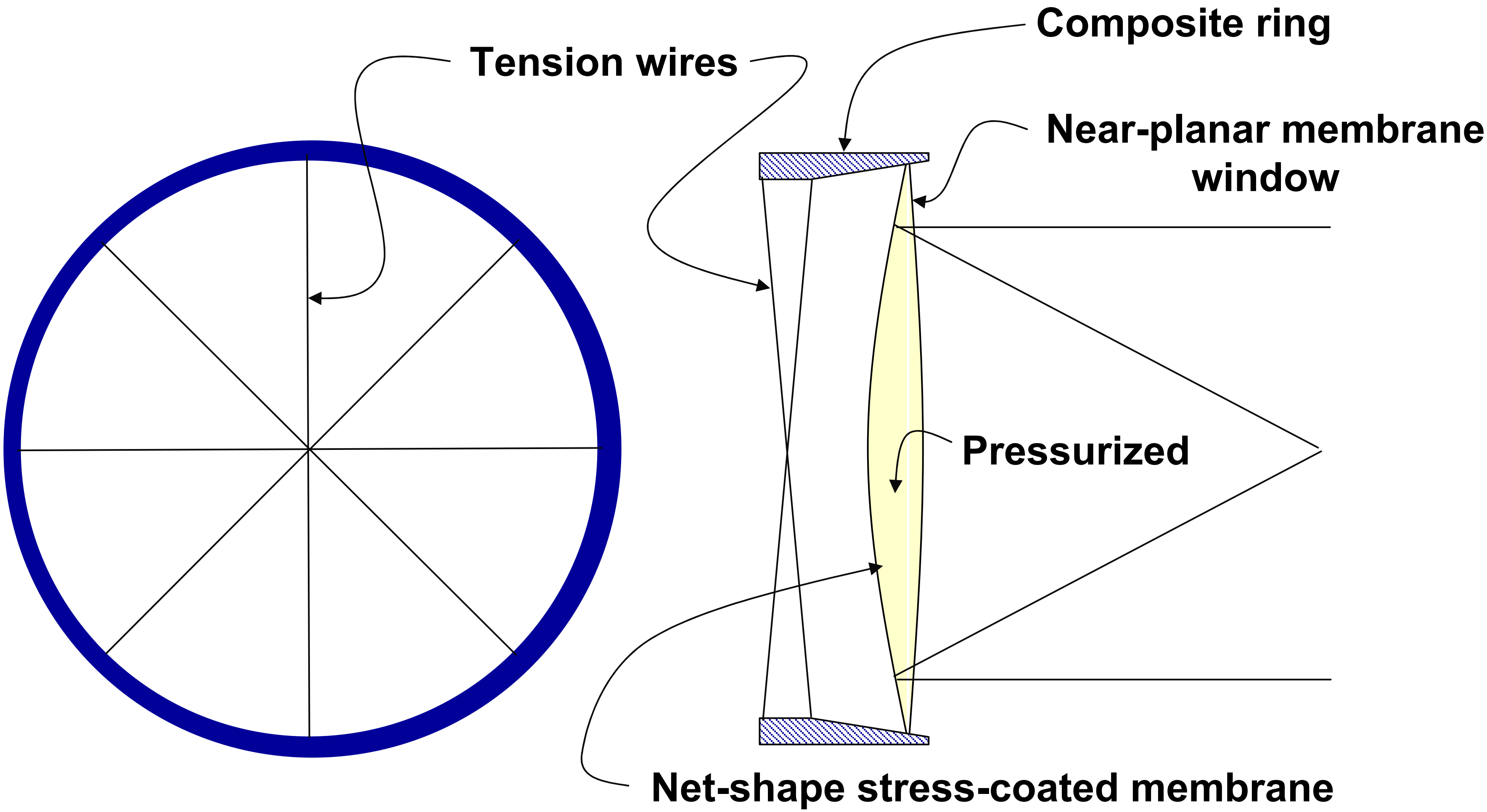
(Wall thickness = 3 mm)		α = 0.01 rad/s^2		α = 0.1 rad/s^2	
Cross-section (mm)	Areal Density (kg/m^2)	w_{max} (μm)	f_0 (Hz)	w_{max} (μm)	f_0 (Hz)
13 X 25	1.152			3.37	55.68
10 X 25	1.044			6.42	40.325
7 X 25	**0.936**			**18.21**	23.94
13 X 13	**0.72**			**4.17**	50.088
7 X 13	**0.504**			**20.50**	22.582



Baseline Design

- Baseline aluminum design of 13 mm X 13 mm (0.5 in X 0.5 in) nearly meets slew displacement and areal density requirements
- Lowest frequency > 100 Hz requirement may be met by placing ring in compression using spokes (see next slide)
- Graphite/epoxy improves compliance with requirements further
- Preliminary mirror is under construction and includes:
    - Electrostatic boundary control
    - Planarity adjustment
    - Under compensated pressure-augmented net-shape membrane

Re-inventing the Wheel



Ultra-lightweight optics

- Membrane Development
- Membrane Mechanics
- Boundary Development
- **Coatings Development**

Vacuum Coatings For Large Aperture Membrane Mirrors

David A. Sheikh

Surface Optics Corporation

Special thanks to John Busbee for ML's earlier work in stress coatings

Surface Optics Corporation's Coating Capabilities

- **Large, 3.3-meter vacuum chamber**
- **6 pocket ebeam evaporation with Mark II Ion Gun**
- **Novel motion controlled evaporation system with rate feed-back for uniform films**
- **(3) smaller vacuum chambers for development and small-scale production**

Optical Measurements

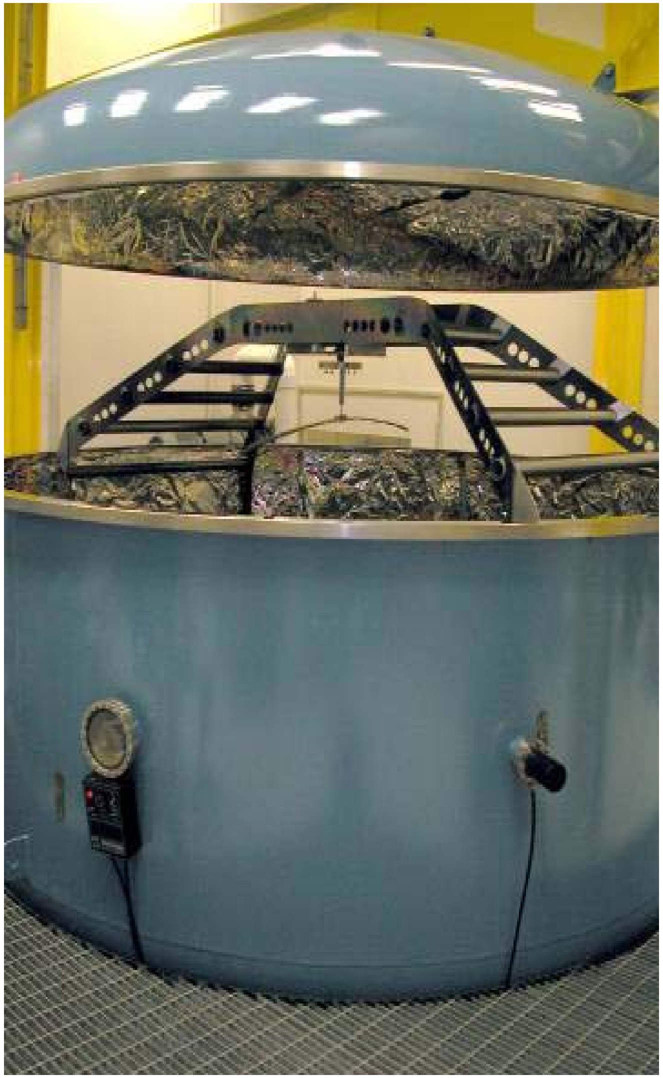
- Reflectivity 0.3 – 2.0 microns (polarized, at angle)
- Hemispherical Reflectance 2 – 100
- BRDF – Scatter measurements as a function of wavelength and angle
- Portable FTIR's
- Real-time Hyperspectral Imaging

Coatings Needed For Membrane Optics

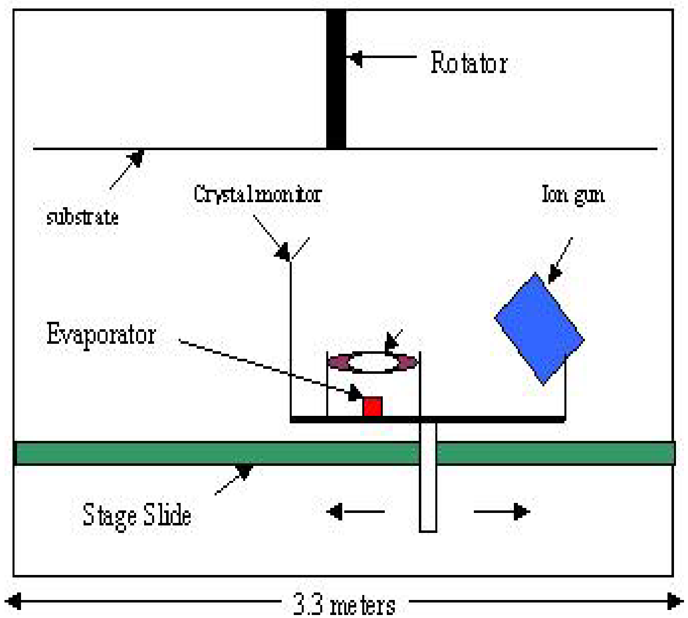
- Reflective
  - Protected Aluminum
  - Dielectric Mirrors
- Wide-Band Anti-Reflection Coatings
- Stress Coatings
- Tailored CTE Coatings
- UV Protective Coatings
- Thermal Control
  - Tailored α/ε

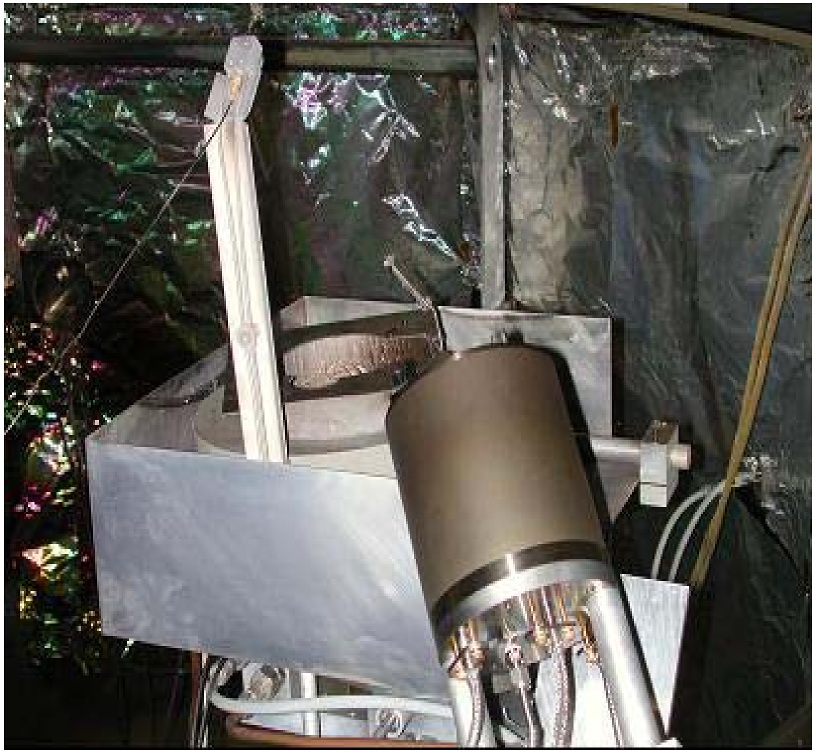
CHA Evaporation System

3.3-meter Vacuum Chamber

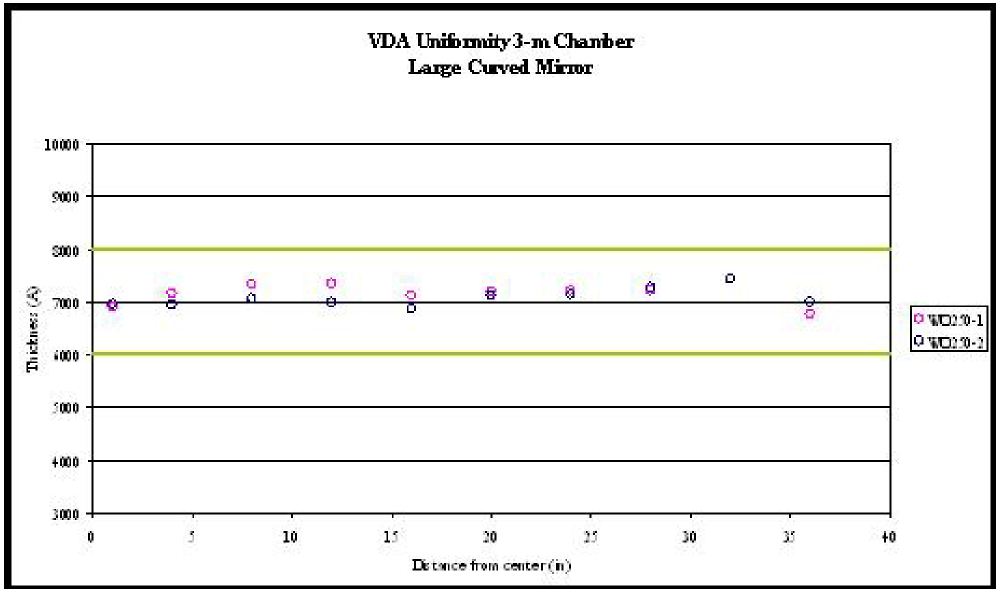


Motion Controlled Evaporation System





Coating Uniformity



- Uniform Films Over Large Areas
  - +/- 3% flat substrates, +/- 4% typical curved optics
  - Programmable thickness (no trial and error)
  - Development underway to improve thickness to +/- 1%

1.5-meter, CP-1 Membrane Mirrors

45-Layer Dielectric Solar Reflector On Kapton™ Film (26 ”x 60”)

Coating Applications

Space Flight
Reflectors

The five enabling Technologies

- Ultra-lightweight optics (including optical windows)*
- Advanced WFC*
- Wide Dynamic range WFS* (UAH?)
- Agile narrowband filters (NMSU)
- **HAA (MDA)**

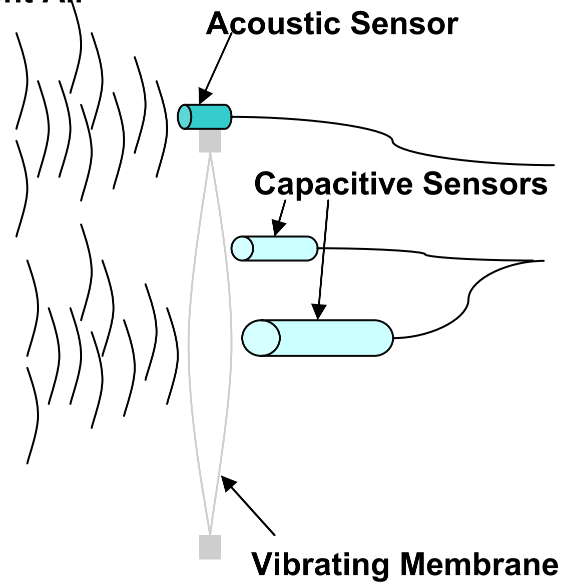
* DE developed technologies

Planned Upper-Atmosphere and Space Experiments

Membrane Mirror Experiment
Upper Atmosphere

EXPERIMENTAL PLATFORMS

High-altitude balloon	**V-Airship**
Lighter-than-air driven	Lighter-than-air/engine driven
Hitchhiker payload	Primary payload
~100,000 ft; ~5 hrs	~120,000 ft; ~5 days; 200 nm
Winter 04	Summer 04



Payload description-

- **One optical membrane mirror**
- **Acoustic sensor will measure turbulence of atmospheric particles**
- **Capacitive sensors will measure time-dependent position data on the order of 100 nanometers**
- **Onboard power, sensing, data-recording capability**
- **Weight: 15kg; Dimensions: 30x30x45 cm; Power: ~50 W**

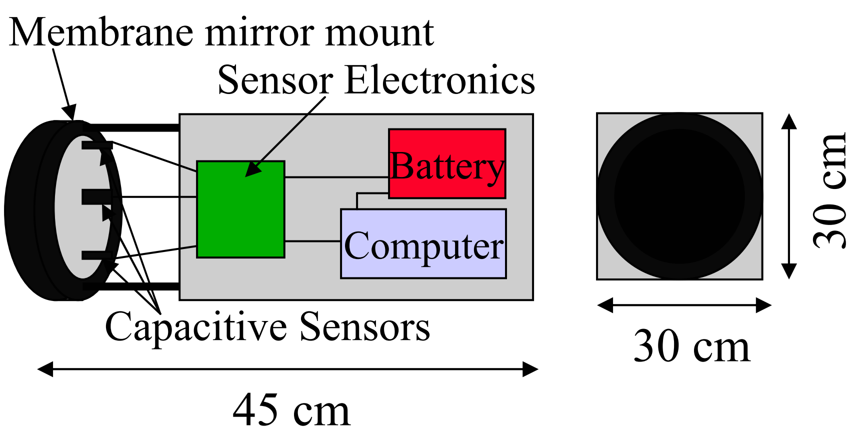
Experimental Objective: To characterize the turbulent acoustic disturbances of the upper atmosphere and how those disturbances affect ultra-lightweight membrane optics

Membrane Mirror Experiment
Low Earth Orbit

<u>Details:</u>
Shuttle/ISS platform preferred
Use of articulating arm critical
Hardware retrieval mandatory
Experiment will verify components for future space missions

AFRL SERB Ranking:
3/21

<u>Military Relevance:</u>
Services/agencies need large optics. Flexible compliant nature allows this



Experimental Payload

- **Planar membrane mirror with composite boumdary**
- **Capacitive sensors will measure time-dependent position data on the order of 100 nm**
- **Payload orientation rotated between ram and wake**
- **Onboard power, sensing and recording equip**

Experimental Objective: To characterize the drag effects of the residual atmosphere at LEO and determine how these disturbances affect ultra-lightweight optics.

Concluding charts

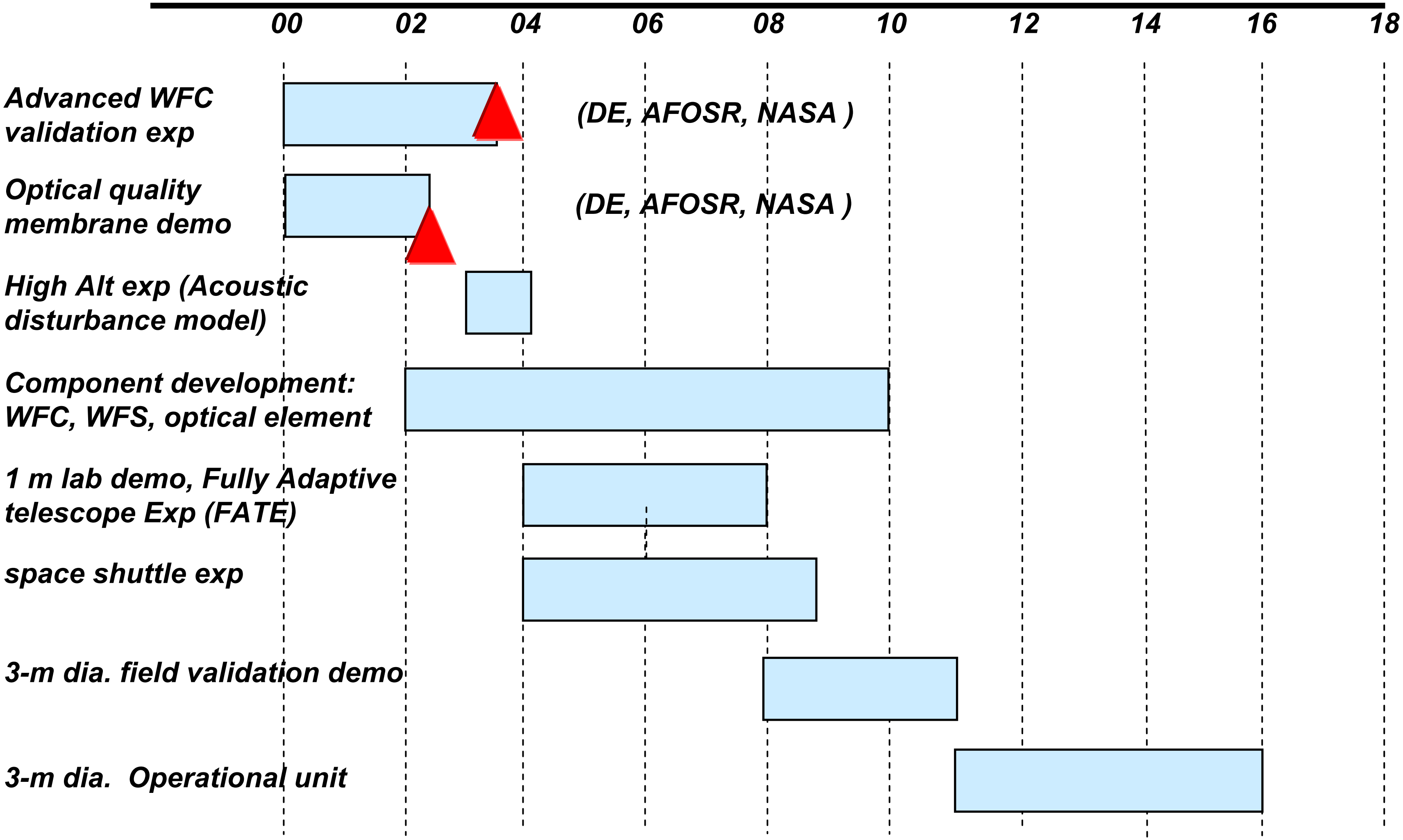
- The five enabling Technologies
  - Varied levels of readiness
  - Technology is ripe for development
- Adaptive films not yet part of the development
- TRL - 5/6 by 2009 for most of the technologies

Technology Readiness

• Membrane optics	
– Windows	TRL 5
– Primary mirror	TRL 3
– Boundaries	TRL 1
• Advanced WFC	
– Spatial light modulators	TRL 4
– MEMS	TRL 3
• Wide dynamic range WFS	
– Moire deflectometer	TRL 4
– Novel WFS	TRL 1
• Agile spectral filters	TRL 3
• Process and control (TBD)	TRL 1

Approximate Schedule

(Notional schedule used only to depict the maturity of the technology)



TBD